NASA HISTORICAL DATA BOOK
Volume VII

NASA Launch Systems, Space Transportation, Human Spaceflight, and Space Science
1989–1998

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Volume VII

NASA Launch Systems, Space Transportation/ Human Spaceflight, and Space Science
1989–1998

Judy A. Rumerman

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CONTENTS

List of Figures and Tables v

Preface and Acknowledgments xvii

About the Author xix

Notes on Sources xxi

Chapter One: Introduction 1

Chapter Two: Launch Systems 17

Chapter Three: Space Transportation/Human Spaceflight 187

Chapter Four: Space Science 571

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LIST OF FIGURES AND TABLES

Chapter One: Introduction

Table 1–1 Programs Within the R&D Appropriation 9
Table 1–2 Centers of Excellence 11
Table 1–3 Program Office Functional Areas 12

Chapter Two: Launch Systems

Figure 2–1 NASA's Fleet of Launch Vehicles 20
Figure 2–2 Office of Space Flight 24
Figure 2–3 Office of Space Flight 25
Figure 2–4 Office of Space Systems Development 26
Figure 2–5 Office of Advanced Concepts and Technology 28
Figure 2–6 Office of Space Access and Technology, September 1994 29
Figure 2–7 Office of Space Flight 31
Figure 2–8 Office of Space Flight 31
Figure 2–9 Expendable Launch Vehicle Success Rate 38
Figure 2–10 Athena I and Athena II 42
Figure 2–11 Atlas I Components 45
Figure 2–12 Atlas IIAS Launch Vehicle 47
Figure 2–13 Delta II Components 52
Figure 2–14 Delta II 7925 53
Figure 2–15 Delta 3920/PAM-D, Delta II 6925, and Delta II 7925 54
Figure 2–16 Delta II Mission Profile 54
Figure 2–17 Pegasus Mounted Under B–52 Wing 56
Figure 2–18 Pegasus Vehicle 57
Figure 2–19 Pegasus XL Mission Profile 58
Figure 2–20 Taurus Launch Vehicle Configuration 60
Figure 2–21 The First Stage of the Titan IV ELV 63
Figure 2–22 Drawing of Space Shuttle External Tank 66
Figure 2–23 Space Shuttle Solid Rocket Booster 68
Figure 2–24 Space Shuttle Main Engine Components 69
Figure 2–25 Ulysses atop the Payload Assist Module-S and IUS Combination 71
Figure 2–26 Pratt & Whitney RL10 Engine 71
Figure 2–27 Atlas-Centaur Upper Stage 73
Figure 2–28 The Magellan Spacecraft with its Attached Inertial Upper Stage Booster 75
Figure 2–29 First Test Flight of the DC-XA 76
Figure 2–30 The X–34 Testbed Demonstrator 82
Figure 2–31 Aerospike Engine 83
Figure 2–32 The X–33 and VentureStar 87

Table 2–1 Authorized/Appropriated Budget (FY 1989–FY 1998) 89
Table 2–2 Programmed Budget (FY 1989–FY 1998) 91

Table 2–3 Space Transportation Capability Development/Payload and Utilization Operations 96
Table 2–4 Upper Stages 97
Table 2–5 Engineering and Technical Base 97
Table 2–6 Payload Operations and Support Equipment 98
Table 2–7 Advanced Programs 98
Table 2–8 Advanced Projects 98
Table 2–9 Tethered Satellite System 99
Table 2–10 Orbital Maneuvering Vehicle 99
Table 2–11 Advanced Concepts and Technology/Space Access and Technology 100
Table 2–12 Advanced Space Transportation 100
Table 2–13 Advanced Transportation Technology/New Launch System 101
Table 2–14 Reusable Launch Vehicle–Systems Engineering and Analysis 102
Table 2–15 Reusable Launch Vehicle–Technology Program 102
Table 2–16 Reusable Launch Vehicle–Initial Flight Demonstration Program (FDP) 102
Table 2–17 X-33 Advanced Technology Demonstrator 102
Table 2–18 X-34 Technology Demonstration Program 103
Table 2–19 Transportation Technology Support 103
Table 2–20 Space Shuttle Production and Operational Capability/Safety and Performance Upgrades 103
Table 2–21 Orbiter (Orbiter Operational Capability) 104
Table 2–22 Systems Integration (Orbiter Operational Capability) 104
Table 2–23 Orbiter Improvements 104
Table 2–24 Extended Duration Orbiter (Orbiter Operational Capability) 105
Table 2–25 Structural Spares (Orbiter Operational Capability) 105
Table 2–26 Orbiter Spares (Orbiter Operational Capability) 105
Table 2–27 Flight Operations Upgrades 106
Table 2–28 Launch Site Equipment (Launch and Mission Support) 106
Table 2–29 Mission Support Capability (Launch and Mission Support) 106
Table 2–30 Mission Operations Capability (Launch and Mission Support) 107
Table 2–31 Mission Operations and Support Capability Funding History 107
Table 2–32 Space Shuttle Main Engine Upgrades 107
Table 2–33 Solid Rocket Booster (Propulsion Systems) 108
Table 2–34 Solid Rocket Booster Improvements 108
Table 2–35 External Tank (Propulsion Systems) 108
Table 2–36 Super Lightweight Tank 108
Table 2–37 Construction of Facilities 109
Table 2–38 Advanced Solid Rocket Motor (Propulsion Systems) 109
Table 2–39 Assured Shuttle Availability 109
Table 2–40 Space Transportation (Space Shuttle) Operations 110
Table 2–41 Mission Support (Flight Operations) 110
Table 2–42 Integration (Flight Operations) 111
Table 2–43 Support (Flight Operations) 111
Table 2–44 Orbiter (Flight Hardware) 111
Table 2–45 Space Shuttle Main Engine (Propulsion Systems) 112

Table 2–46 Solid Rocket Booster (Flight Hardware) 112
Table 2–47 Redesigned Solid Rocket Motor (Flight Hardware) 113
Table 2–48 External Tank (Flight Hardware) 113
Table 2–49 Launch and Landing Operations 113
Table 2–50 Launch Operations (Launch and Landing Operations) 114
Table 2–51 Payload and Launch Support (Launch and Landing Operations) 114
Table 2–52 Expendable Launch Vehicles and Services 115
Table 2–53 Small Class (Expendable Launch Vehicles and Services) 115
Table 2–54 Medium Class (Expendable Launch Vehicles and Services) 116
Table 2–55 Intermediate Class (Expendable Launch Vehicles and Services) 116
Table 2–56 Large Class (Expendable Launch Vehicles and Services) 117
Table 2–57 Launch Services Mission Support 117
Table 2–58 Expendable Launch Vehicle Success Rate by Year and Launch Vehicle 118
Table 2–59 Athena Launches (1989–1998) 119
Table 2–60 Athena I Characteristics 120
Table 2–61 Athena II Characteristics 121
Table 2–62 Atlas Launches (1989–1998) 122
Table 2–63 Atlas E Characteristics 127
Table 2–64 Atlas G Centaur Characteristics 128
Table 2–65 Atlas I Characteristics 129
Table 2–66 Typical Atlas Launch Events Sequence for a Geosynchronous Mission 130
Table 2–67 Atlas II Characteristics 131
Table 2–68 Atlas IIA Characteristics 132
Table 2–69 Atlas IIAS Characteristics 133
Table 2–70 Conestoga 1620 Characteristics 135
Table 2–71 Delta Launches (1989–1998) 136
Table 2–72 Delta 3920/PAM-D Characteristics 142
Table 2–73 Delta II 6925 Characteristics 143
Table 2–74 Delta 7925 Characteristics 144
Table 2–75 Representative Delta II Mission Profile Events 145
Table 2–76 Pegasus Launches (1989–1998) 146
Table 2–77 Standard Pegasus Characteristics 149
Table 2–78 Pegasus XL Characteristics 150
Table 2–79 Scout G1 Characteristics 151
Table 2–80 Scout Launches (1989–1998) 152
Table 2–81 Taurus 2210 Characteristics 153
Table 2–82 Taurus Launches (1989–1998) 154
Table 2–83 Titan Launches (1989–1998) 155
Table 2–84 Titan II Characteristics 158
Table 2–85 Space Shuttle Flights (1989–1998) 159
Table 2–86 External Tank Characteristics 165
Table 2–87 Solid Rocket Booster Characteristics 166
Table 2–88 Space Shuttle Main Engine Characteristics 166
Table 2–89 Titan Centaur Upper Stage Characteristics 167

Table 2–90 Inertial Upper Stage Characteristics 167
Table 2–91 Inertial Upper Stage Launches 168
Table 2–92 DC-X Characteristics 169
Table 2–93 DC-X and DC-XA Flight Tests 170
Table 2–94 X-34 Characteristics 171
Table 2–95 X-33 Characteristics 171
Table 2–96 Reusable Launch Vehicle Chronology 172

Chapter Three: Human Spaceflight

Figure 3–1 Space Shuttle Program Organization, December 1997 195
Figure 3–2 Space Shuttle Program Elements and Projects, December 1997 195
Figure 3–3 Headquarters Office of Space Station, December 1988 197
Figure 3–4 Tiered Space Station Organizational Structure, April 1989 198
Figure 3–5 Marshall Space Flight Center Space Station Organization, April 1989 199
Figure 3–6 Johnson Space Center Space Station Organization, April 1989 200
Figure 3–7 Goddard Space Flight Center Space Station Organization, April 1989 201
Figure 3–8 Lewis Research Center Space Station Organization, April 1989 201
Figure 3–9 Kennedy Space Center Space Station Organization, April 1989 202
Figure 3–10 Space Station Freedom Program Office, May 1990 204
Figure 3–11 Office of Space Systems Development 205
Figure 3–12 Space Station *Freedom* Three-Level Program Management, 1992 207
Figure 3–13 Space Station *Freedom* Work Package and International Partner Development Responsibilities 207
Figure 3–14 Office of Space Flight, October 1995 209
Figure 3–15 Space Shuttle Vehicle Configuration 216
Figure 3–16 Orbiter Structure 218
Figure 3–17 Spacelab on Orbit 224
Figure 3–18 Spacelab Components 225
Figure 3–19 Typical SPACEHAB Interior Configurations 229
Figure 3–20 SPACEHAB Configuration 1 230
Figure 3–21 SPACEHAB Configurations 2 (top) and 3 231
Figure 3–22 Extravehicular Mobility Unit (Spacesuit) 235
Figure 3–23 Astronaut F Story Musgrave 236
Figure 3–24 The Long Duration Exposure Facility (LDEF) 241
Figure 3–25 The Gamma Ray Observatory 243
Figure 3–26 On Board Space Shuttle *Discovery* 245
Figure 3–27 ATLAS-1 Payload Configuration 246
Figure 3–28 Tethered Satellite System (TSS-1) Deployment 248
Figure 3–29 TDRS-F (6) On-Orbit Configuration 250
Figure 3–30 Space Shuttle *Columbia* Blasts Off 251

Figure 3–31 EURECA Mission Scenario 253
Figure 3–32 ORFEUS-SPAS and ACTS/TOS 254
Figure 3–33 ORFEUS-SPAS Configuration 254
Figure 3–34 The SIR and X-SAR 257
Figure 3–35 Payloads on STS-59 257
Figure 3–36 IML-2 Module Racks 259
Figure 3–37 *Mir* Space Station with *Discovery* 262
Figure 3–38 SPARTAN-204 263
Figure 3–39 Astro-2 Suite of Telescopes 264
Figure 3–40 The SPAS-2 271
Figure 3–41 The SPACEHAB Double Module 273
Figure 3–42 Dave Williams with the Virtual Environment Generator on *Columbia* 275
Figure 3–43 Space Station *Freedom* Configuration 285
Figure 3–44 U.S. Laboratory Module 285
Figure 3–45 U.S. Habitation Module 286
Figure 3–46 European Space Agency Attached Pressurized Module 286
Figure 3–47 Japanese Experiment Module 287
Figure 3–48 Japanese Experiment Module Exposed Facility 289
Figure 3–49 Canada's Special Purpose Dexterous Manipulator (SPDM) 289
Figure 3–50 Man-Tended Capability 290
Figure 3–51 Permanently Manned Capability Configuration 291
Figure 3–52 Space Station *Freedom* Assembly Stages 292
Figure 3–53 *Mir* Space Station 299
Figure 3–54 *Atlantis* Docked with *Mir* 301
Figure 3–55 Undocking of *Atlantis* and *Mir* 302
Figure 3–56 Processing of Leonardo, the First Multi-Purpose Logistics Module 311
Figure 3–57 Commemorative Plaque, ISS Agreements 316
Figure 3–58 The Unity Module Inside *Endeavour* 318
Figure 3–59 Diagram of Unity Connecting Module 319
Figure 3–60 Construction of the International Space Station 319
Figure 3–61 Unity and Zarya Modules 320
Figure 3–62 Artist's conception of Completed ISS 321
Figure 3–63 Drawing Showing the Completed ISS and Contributions by each of the International Partners, 1998 322
Figure 3–64 X-38 Flight Test 323

Table 3–1 Percent of NASA's R&D or HSF Budget Allocated for Space Station 324
Table 3–2 Authorized/Appropriated Budget (FY 1989–FY 1998) 325
Table 3–3 Programmed Budget (FY 1989–1998) 327
Table 3–4 Spacelab Funding History 332
Table 3–5 Space Station (Total) Funding History 333
Table 3–6 U.S./Russian Cooperative Program Funding History 334
Table 3–7 Russian Space Agency Contract Support Funding History 335
Table 3–8 *Mir* Support Funding History 335
Table 3–9 Russian Program Assurance Funding History 335

Table 3–10 Space Station Development Funding History 336
Table 3–11 Development–Management and Integration Funding History 336
Table 3–12 Development–Pressurized Modules Funding History 337
Table 3–13 Development–Assembly Hardware/Subsystem Funding History 337
Table 3–14 Development–Platforms and Servicing Funding History 337
Table 3–15 Development–Power Systems Funding History 338
Table 3–16 Development–Operations/Utilization Capability Funding History 338
Table 3–17 Development–Flight Hardware Funding History 338
Table 3–18 Development–Test, Manufacturing and Assembly Funding History 339
Table 3–19 Development–Operations Capability and Construction Funding History 339
Table 3–20 Development–Transportation Support Funding History 339
Table 3–21 Development–Flight Technology Demonstrations Funding History 340
Table 3–22 Development–Operations Capability and Construction Funding History 340
Table 3–23 Shuttle/Spacelab Payload Mission Management and Integration Funding History 340
Table 3–24 Space Station Integration Planning and Attached Payloads Funding History 341
Table 3–25 Assured Crew Return Vehicle Funding History 341
Table 3–26 Flight Telerobotic System/Servicer Funding History 341
Table 3–27 Space Station Utilization Support Funding History 342
Table 3–28 Space Station Operations Funding History 342
Table 3–29 Space Station Research Funding History 343
Table 3–30 Space Station Transition Definition/Advanced Programs Funding History 343
Table 3–31 Life Sciences Funding History 344
Table 3–32 Life Sciences Flight Experiments Funding History 344
Table 3–33 Human Spaceflight and Systems Engineering Funding History 345
Table 3–34 Space Biological Sciences Funding History 345
Table 3–35 Life Sciences Research and Analysis Funding History 345
Table 3–36 Lifesat/Radiation Biology Initiative History 346
Table 3–37 Life and Microgravity Sciences (Total) Funding History 346
Table 3–38 Centrifuge Funding History 346
Table 3–39 Search for Extraterrestrial Intelligence Funding History 347
Table 3–40 Life Sciences Flight Program Funding History 347
Table 3–41 Advanced Human Support Technology Program Funding History 347
Table 3–42 Biomedical Research and Countermeasures Program Funding History 348
Table 3–43 Gravitational Biology and Ecology Program Funding History 348

Table 3–44	Orbiter Characteristics	349
Table 3–45	*Endeavour* Construction Milestones	350
Table 3–46	Space Shuttle Payload Accommodation	351
Table 3–47	Spacelab Module Characteristics	353
Table 3–48	Spacelab Missions	354
Table 3–49	SPACEHAB Missions	355
Table 3–50	Space Shuttle Extravehicular Activity (1989–1998)	356
Table 3–51	Space Shuttle Missions Summary (1989–1998)	360
Table 3–52	STS-29 Mission Characteristics	376
Table 3–53	STS-30 Mission Characteristics	379
Table 3–54	STS-28 Mission Characteristics	380
Table 3–55	STS-34 Mission Characteristics	382
Table 3–56	STS-33 Mission Characteristics	384
Table 3–57	STS-32 Mission Characteristics	385
Table 3–58	STS-36 Mission Characteristics	387
Table 3–59	STS-31 Mission Characteristics	388
Table 3–60	STS-41 Mission Characteristics	390
Table 3–61	STS-38 Mission Characteristics	392
Table 3–62	STS-35 Mission Characteristics	394
Table 3–63	STS-37 Mission Characteristics	399
Table 3–64	STS-39 Mission Characteristics	401
Table 3–65	STS-40 Mission Characteristics	403
Table 3–66	STS-43 Mission Characteristics	409
Table 3–67	STS-48 Mission Characteristics	411
Table 3–68	STS-44 Mission Characteristics	413
Table 3–69	STS-42 Mission Characteristics	415
Table 3–70	STS-45 Mission Characteristics	420
Table 3–71	STS-49 Mission Characteristics	422
Table 3–72	STS-50 Mission Characteristics	425
Table 3–73	STS-46 Mission Characteristics	427
Table 3–74	STS-47 Mission Characteristics	429
Table 3–75	STS-52 Mission Characteristics	435
Table 3–76	STS-53 Mission Characteristics	438
Table 3–77	STS-54 Mission Characteristics	440
Table 3–78	STS-56 Mission Characteristics	441
Table 3–79	STS-55 Mission Characteristics	444
Table 3–80	STS-57 Mission Characteristics	449
Table 3–81	STS-51 Mission Characteristics	453
Table 3–82	STS-58 Mission Characteristics	455
Table 3–83	STS-61 Mission Characteristics	458
Table 3–84	STS-60 Mission Characteristics	460
Table 3–85	STS-62 Mission Characteristics	464
Table 3–86	STS-59 Mission Characteristics	467
Table 3–87	STS-65 Mission Characteristics	469
Table 3–88	STS-64 Mission Characteristics	471
Table 3–89	STS-68 Mission Characteristics	476
Table 3–90	STS-66 Mission Characteristics	479
Table 3–91	STS-63 Mission Characteristics	482

Table 3–92	STS-67 Mission Characteristics	485
Table 3–93	STS-71 Mission Characteristics	487
Table 3–94	STS-70 Mission Characteristics	489
Table 3–95	STS-69 Mission Characteristics	491
Table 3–96	STS-73 Mission Characteristics	494
Table 3–97	STS-74 Mission Characteristics	496
Table 3–98	STS-72 Mission Characteristics	498
Table 3–99	STS-75 Mission Characteristics	500
Table 3–100	STS-76 Mission Characteristics	502
Table 3–101	STS-77 Mission Characteristics	505
Table 3–102	STS-78 Mission Characteristics	508
Table 3–103	STS-79 Mission Characteristics	512
Table 3–104	STS-80 Mission Characteristics	514
Table 3–105	STS-81 Mission Characteristics	517
Table 3–106	STS-82 Mission Characteristics	519
Table 3–107	STS-83 Mission Characteristics	521
Table 3–108	STS-84 Mission Characteristics	523
Table 3–109	STS-94 Mission Characteristics	525
Table 3–110	STS-85 Mission Characteristics	528
Table 3–111	STS-86 Mission Characteristics	531
Table 3–112	STS-87 Mission Characteristics	533
Table 3–113	STS-89 Mission Characteristics	536
Table 3–114	STS-90 Mission Characteristics	538
Table 3–115	STS-91 Mission Characteristics	541
Table 3–116	STS-95 Mission Characteristics	545
Table 3–117	STS-88 Mission Characteristics	549
Table 3–118	Space Station *Freedom* Prime Contractor	552
Table 3–119	Space Station *Freedom* Characteristics	553
Table 3–120	Shuttle-Mir Flights	555
Table 3–121	ISS Contributor	556
Table 3–122	ISS Major Milestones (as of April 1994)	557
Table 3–123	ISS Assembly Schedule (June 1994)	557
Table 3–124	Columbus Characteristics	558
Table 3–125	Partial Revised Manifest, Revision C, Through 1999 (as of 15 May 1997)	559
Table 3–126	ISS Assembly Sequence Revision D, Through 1999	560
Table 3–127	Functional Cargo Block (Zarya) Specification	561
Table 3–128	Unity Characteristic	561
Table 3–129	Zarya-Unity Orbital Events Summary	562
Table 3–130	Science Laboratories Accommodations	563
Table 3–131	Space Station Chronology	564

Chapter Four: Space Science

Figure 4–1	Office of Space Science and Applications, 1981–1993	581
Figure 4–2	Office of Space Science, 1993	583
Figure 4–3	Office of Space Science, November 1995	585
Figure 4–4	COBE Configuration	594

Figure 4–5 COBE's Infrared View of the Universe 596
Figure 4–6 EUVE Spacecraft 597
Figure 4–7 SAMPEX Spacecraft 599
Figure 4–8 Rossi X-Ray Timing Explorer 602
Figure 4–9 FAST Small Explorer Satellite 603
Figure 4–10 ACE L1 Orbit 606
Figure 4–11 Expanded View of ACE 607
Figure 4–12 SNOE Spacecraft Structure 609
Figure 4–13 Filament Eruption Observed by TRACE 611
Figure 4–14 SWAS Telescope 612
Figure 4–15 ROSAT Spacecraft 616
Figure 4–16 ROSAT Spacecraft Configuration 618
Figure 4–17 HST's "First Light" Image 622
Figure 4–18 Images of Spiral Galaxy M100 624
Figure 4–19 Light Path for the Main Telescope 626
Figure 4–20 Hubble Space Telescope Configuration 627
Figure 4–21 First Servicing Mission of HST 630
Figure 4–22 Close-up of HST 633
Figure 4–23 HST Image of Jupiter 635
Figure 4–24 Ring Structure Around Supernova 1987A 636
Figure 4–25 HST Image of Eta Carinae 637
Figure 4–26 HST Image of Supernova 1987A Debris 638
Figure 4–27 G1 Orbits the Andromeda Galaxy 639
Figure 4–28 Black Holes 640
Figure 4–29 Collision of Two Galaxies 641
Figure 4–30 Quasar Host Galaxies 642
Figure 4–31 Spiral Galaxy NGC 4603 642
Figure 4–32 Image of Gamma-Ray Burst GRB 970228 643
Figure 4–33 Supernovae 644
Figure 4–34 Release of the GRO Spacecraft 645
Figure 4–35 Compton Gamma Ray Observatory 647
Figure 4–36 Chandra Optical Bench Assembly at TRW 655
Figure 4–37 Chandra X-Ray Observatory 656
Figure 4–38 Ulysses Primary Mission 663
Figure 4–39 Ulysses Configuration 663
Figure 4–40 Deep Space 1 Spacecraft 670
Figure 4–41 Geotail Spacecraft Configuration 676
Figure 4–42 Wind Spacecraft 677
Figure 4–43 Location of Polar Spacecraft Instruments 680
Figure 4–44 SOHO Images 682
Figure 4–45 Yohkoh Images of the Solar Cycle 685
Figure 4–46 IUE Images 688
Figure 4–47 The Four-Stage Black Brant 692
Figure 4–48 A Scientific Balloon Ready for Launch 694
Figure 4–49 Magellan Earth-to-Venus Trajectory 695
Figure 4–50 Magellan Venus Orbital Operations 696
Figure 4–51 Magellan Spacecraft 699
Figure 4–52 Magellan Radar Image of Venusian Volcano 700

Figure 4–53 Magellan Radar Image of Venusian Crater 701
Figure 4–54 Galileo Spacecraft 702
Figure 4–55 Galileo Trajectory 703
Figure 4–56 Galileo Image of Asteroid 951 Gaspra 705
Figure 4–57 Galileo Image of Asteroid 243 Ida 707
Figure 4–58 Comet Collides with Jupiter 707
Figure 4–59 Galileo Probe Mission to Jupiter 708
Figure 4–60 Galileo's Primary Mission Orbits 711
Figure 4–61 Lunar Prospector Mission Profile 719
Figure 4–62 Artist's Conception of Lunar Prospector About to Impact the Moon 720
Figure 4–63 South Pole of the Moon 723
Figure 4–64 Mars Global Surveyor 727
Figure 4–65 Martian "Face" 729
Figure 4–66 Light and Dark Layers in Martian Canyon Walls 730
Figure 4–67 Mars Pathfinder Entry, Descent and Landing 731
Figure 4–68 Mars Pathfinder's Sojourner Microrover 732
Figure 4–69 Mars Pathfinder Lander 734
Figure 4–70 Mars Climate Orbiter 737
Figure 4–71 Radioisotope Thermoelectric Generator 742
Figure 4–72 Cassini Interplanetary Trajectory 743
Figure 4–73 Cassini Spacecraft 745
Figure 4–74 Pioneer 10 and Pioneer 11 Pictorial Plaque 747
Figure 4–75 Voyager 2 Image of Neptune's Rings 749
Figure 4–76 The SPARTAN 201–04 Satellite 760
Figure 4–77 ORFEUS-SPAS II 762
Figure 4–78 ORFEUS-SPAS I Configuration 765

Table 4–1 Space Science Launched Missions (1989–1998) 767
Table 4–2 Attached/Retrieved NASA Space Science Missions 774
Table 4–3 Authorized Budget (FY 1989–FY 1998) 776
Table 4–4 Programmed Budget (FY 1989–1998) 777
Table 4–5 Physics and Astronomy Funding History 778
Table 4–6 Hubble Space Telescope Development Funding History 778
Table 4–7 Gamma Ray Observatory Funding History 778
Table 4–8 Global Geospace Science Funding History 779
Table 4–9 Advanced X-Ray Astrophysics Facility Funding History 779
Table 4–10 Payload and Instrument Development Funding History 780
Table 4–11 Shuttle/Spacelab Payload Mission Management and Integration Funding History 780
Table 4–12 Explorer Development Funding History 781
Table 4–13 Physics and Astronomy Mission Operations and Data Analysis Funding History 781
Table 4–14 Physics and Astronomy Research and Analysis Funding History 782
Table 4–15 Space Science Supporting Research and Technology Funding History 782

Table 4–16 Space Infrared Telescope Facility (SIRTF) Funding History 782
Table 4–17 Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) Funding History 783
Table 4–18 Stratospheric Observatory for Infrared Astronomy Funding History 783
Table 4–19 Suborbital Program Funding History 783
Table 4–20 Gravity Probe-B Development/Relativity Mission Funding History 784
Table 4–21 Information Systems Funding History 784
Table 4–22 Planetary Exploration Funding History 784
Table 4–23 Galileo Development Funding History 785
Table 4–24 Ulysses Funding History 785
Table 4–25 Magellan Funding History 785
Table 4–26 Mars Observer Funding History 785
Table 4–27 Planetary Exploration Mission Operations and Data Analysis Funding History 786
Table 4–28 Planetary Exploration Research and Analysis Funding History 786
Table 4–29 Comet Rendezvous Asteroid Flyby (CRAF)/Cassini Funding History 787
Table 4–30 Mars Balloon Relay Experiment Funding History 787
Table 4–31 Mars ‘94 Funding History 788
Table 4–32 Discovery Funding History 788
Table 4–33 Mars Surveyor Funding History 789
Table 4–34 Space Science New Millennium Funding History 789
Table 4–35 Advanced Space Technology Funding History 789
Table 4–36 Explorer Missions (1989–1998) 790
Table 4–37 Cosmic Background Explorer Mission Characteristics 791
Table 4–38 Extreme Ultraviolet Explorer Mission Characteristics 793
Table 4–39 Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics 796
Table 4–40 Rossi X-Ray Timing Explorer Mission Characteristics 801
Table 4–41 Fast Auroral Snapshot Explorer Mission Characteristics 804
Table 4–42 Advanced Composition Explorer Mission Characteristics 806
Table 4–43 Student Nitric Oxide Explorer Mission Characteristics 810
Table 4–44 Transition Region and Coronal Explorer Mission Characteristics 812
Table 4–45 Submillimeter Wave Astronomy Satellite Mission Characteristics 814
Table 4–46 Roentgen Satellite Mission Characteristics 816
Table 4–47 Combined Release and Radiation Effects Satellite Mission Characteristics 819
Table 4–48 Hubble Space Telescope Mission Characteristics 823
Table 4–49 Compton Gamma Ray Observatory Mission Characteristics 833
Table 4–50 Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics 838

Table 4–51 Ulysses Milestones Characteristics 842
Table 4–52 Ulysses Mission Characteristics 843
Table 4–53 ASCA/Astro-D Mission Characteristics 849
Table 4–54 BeppoSAX Mission Characteristics 854
Table 4–55 Deep Space 1/SEDSAT Mission Characteristics 856
Table 4–56 High Energy Transient Experiment, Satelite de Aplicaciones Cientificas-B Dual Mission Characteristics 860
Table 4–57 Geotail Mission Characteristics 862
Table 4–58 Wind Mission Characteristics 866
Table 4–59 Polar Mission Characteristics 871
Table 4–60 Solar and Heliospheric Observatory Mission Characteristics 875
Table 4–61 Solar-A/Yohkoh Mission Characteristics 879
Table 4–62 NASA Sounding Rocket Launches (1989–1998) 882
Table 4–63 NASA Balloon Flights (1989–1998) 906
Table 4–64 Magellan Mission Events 926
Table 4–65 Magellan Mission Characteristics 927
Table 4–66 Galileo Major Mission Events (1989–1999) 930
Table 4–67 Galileo Encounters at Jupiter (1995–1999) 931
Table 4–68 Galileo Mission Characteristics 932
Table 4–69 *Discovery* Missions Approved by NASA, 1993–1998 938
Table 4–70 Near Earth Asteroid Rendezvous Mission Characteristics 939
Table 4–71 Lunar Prospector Mission Characteristics 944
Table 4–72 Clementine Mission Characteristics 948
Table 4–73 Mars Observer Mission Characteristics 952
Table 4–74 Mars Global Survey Mission Characteristics 954
Table 4–75 Mars Pathfinder Mission Characteristics 960
Table 4–76 Mars '96 Instruments 964
Table 4–77 Mars Climate Orbiter Mission Characteristics 967
Table 4–78 Mars Polar Lander Mission Characteristics 969
Table 4–79 Cassini-Huygens Mission Characteristics 971
Table 4–80 Voyager Events 980
Table 4–81 Astro Mission Characteristics 981
Table 4–82 Astro-2 HUT Scientific Achievements 984
Table 4–83 Spartan 201 Mission Characteristics 987
Table 4–84 ORFEUS-SPAS Science Payload 988

PREFACE AND ACKNOWLEDGMENTS

This volume of the NASA Historical Data Book is the seventh in the series that describes NASA's programs and projects. Covering the years 1989 through 1998, it includes the areas of launch systems, human spaceflight, and space science, continuing the volumes that addressed these topics during NASA's previous decades. Each chapter presents information, much of it statistical, addressing funding, management, and details of programs and missions. This decade, which followed the Agency's return to flight after the *Challenger* accident, was especially productive. Upgraded expendable launch vehicles sent missions into Earth orbit and toward the outer reaches of space; 66 Space Shuttle missions were successfully launched; the Space Station received its first components; and 30 space science missions, most of which met their scientific goals, began returning scientific data to Earth. These events took place in an environment both of international cooperation and one in which NASA learned to make the best use possible of its resources.

A forthcoming companion volume will describe NASA's Earth science missions; aeronautics and space research activities; tracking and space operations; facilities; resources; and personnel areas.

A large group of people assisted in preparing this volume and should be recognized. Most valuable and essential was my research assistant, Tai Edwards, who gathered material, organized it superbly, entered data into tables, and proofed and edited draft chapters, all while attending graduate school and getting married. It would have been impossible to deal with the quantity of information I faced without her help. The NASA History Division archivists, Colin Fries, John Hargenrader, Liz Suckow, and chief archivist Jane Odom, helped gather information. Stephen Garber managed the project and dealt with contractual matters. Interns Matt Barrow and Clare Kim also helped shepherd this project through the production cycle. Nadine Andreassen assisted in a myriad of ways.

On the production end, special thanks go to the NASA Headquarters Communications Support Services Center: Shelley Kilmer-Gaul carefully laid out this volume; Andrew Jarvis edited the layout; and Hanta Ralay oversaw the critical final step of printing. Many thanks are due to all these professionals.

Many people at NASA and in the NASA community gladly provided information and helped explain events and resolve discrepancies. Staff members at every NASA Center willingly offered their assistance and supplied material. Individuals in the program offices at Headquarters and in the various projects at Goddard Space Flight Center spent hours talking with me and finding documents. Graphics personnel both at Headquarters and at the Centers regularly filled my requests for "high resolution graphics."

A special thanks goes to the reviewers of the draft chapters. They took on the arduous job of reading drafts that often numbered in the hundreds of pages, finding errors, and making valuable suggestions.

Their work improved the quality of this document immensely.

I'd also like to thank my husband, Howard, who provided continual support, would listen to my concerns, and frequently resolved computer issues that could have proven disastrous.

ABOUT THE AUTHOR

Judith A. Rumerman is a professional technical writer who has written or contributed to numerous documents for the National Aeronautics and Space Administration. She has written documents describing various spaceflight programs, in-house procedures used at Goddard Space Flight Center, and various materials used for training. She was also the compiler of *U.S. Human Spaceflight: A Record of Achievement, 1961–1998*, a monograph for the NASA History Office detailing NASA's human spaceflight missions, and volumes five and six of the *NASA Historical Data Book, 1979–1988*. In the years preceding the 2003 Centennial of Flight, Ms. Rumerman served as technical lead and prime author of the series of essays written for the Centennial of Flight Commission describing all aspects of aviation and spaceflight aimed at young people of high-school age.

Ms. Rumerman has degrees from the University of Michigan and George Washington University. She grew up in Detroit and presently lives in Silver Spring, Maryland.

NOTES ON SOURCES

The bulk of sources used in preparing this volume are official NASA documents and references. Whenever possible, the author attempted to use primary sources prepared by the organizations or individuals most directly involved in a program or mission. NASA Web sites were also used extensively. Secondary sources were most often used to provide perspective rather than data The following paragraphs describe major sources. Detailed footnotes are located in each chapter.

Annual Budget Estimates: These documents are issued each year by the NASA Office of the Chief Financial Officer when the annual budget request is presented to Congress. These lengthy documents, filling several loose-leaf binders each year, contain breakdowns of three fiscal years of budgets: the year just ending, the next fiscal year, and the fiscal year two years out. Budget figures are presented by appropriation, program office, installation, program, and in any other way that may be of interest to budget preparers. Toward the end of this decade, "full cost" accounting was adopted, and budget figures for major programs were presented in both the traditional way and in "full-cost" figures. The budget estimate documents also provided comprehensive narrative descriptions of programs and activities, describing both what had occurred during a prior fiscal year (and occasionally farther back) and what the Agency's plans were for the next two years. These descriptions provide a useful account of a program's evolution.

Press and Media Kits: NASA prepares press or media kits for every Space Shuttle mission and for a number of major robotic missions. They describe launch events, payloads, planned experiments, astronaut biographies, and other mission-unique information. Designed for non-technical audiences and the media, they provide a comprehensive description of NASA missions. All Shuttle press kits and most other press kits are available online.

Mission Operation Reports: Every NASA mission is required to prepare a pre-launch and post-launch mission operation report. These reports are designed for the use of senior management and, while they are part of the NASA Historical Reference Collection, they may not always be available to the public. They provide material similar to that found in the press kits but may also include more technical information, and the post-launch reports may include assessments of the success of various mission elements.

Aeronautics and Space Reports of the President: These annual reports describe the aeronautics and space activities of all government agencies that engage in these types of activities. They provide a good overview and an excellent starting point for research.

Press Releases: NASA Headquarters and each NASA Center regularly issue press releases describing newsworthy events.They provide the current status on various events including scientific missions, management and organizational changes, contract awards, and changing Agency priorities. They are often the only source of current, detailed information about a mission. Headquarters press releases have been posted on the NASA Web site since the early 1990s. The Centers began posting their press releases in the mid-1990s.

Exploring the Unknown, Selected Documents in the History of the U.S. Civil Space Program, Volume V: Exploring the Cosmos and Volume VI: Space and Earth Science, edited by John Logsdon: Particularly in the space science area, the introductory essays preceding the documents in these two volumes, written by eminent individuals in their fields, provide outstanding descriptions of the major events in the history of the space program.

International Reference Guide to Space Launch Systems, Third Edition and Fourth Edition, by Steven J. Isakowitz, Joseph P. Hopkins, Jr., and Joshua B. Hopkins: Published by the AIAA, the two editions of this reference contain thorough descriptions of every launch vehicle used during this decade, as well as information related to performance, cost, flight history, vehicle design, payload accommodations, production and launch operations, and vehicle history.

Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program, by Howard McCurdy: This book offers an excellent introduction to NASA's management approach, describing what very likely was the dominant philosophy at NASA during this decade.

Web Sites: The past few years have seen an explosion of material posted on the Internet. Every NASA program has a Web site (too many to list here) and posts a wide variety of information about a project. This has had both positive and negative consequences. On the positive side, official documents such as legislation, policies, Agency reports, and directives are readily available. NASA programs post huge amounts of material describing all phases of missions including: mission parameters and specifications, instrument descriptions, scientific results, implications, etc. This information enables researchers to acquire a great deal of information without the need to cull through files or archives. However, it is also very easy for errors to be perpetuated, even when information is located on NASA Web sites. Information is easily copied from one Web site to the next, often without question, and errors are inadvertently introduced when material is not carefully edited. It is necessary for the researcher to verify information carefully before using it. Another issue is the removing of information from Web sites because of storage considerations without archiving the information. Information "disappears" or is moved to another location on the internet. This happens especially when information becomes "out-of-date" without concern for the historical value of the material. Broken links, due both to technical difficulties and the removal or moving of Web pages without revising the referring link, are also a problem. Web material has been used extensively in this volume, but care has been taken to ensure its reliability. An "access" date is always included, and a printed copy of all Web pages used has been provided to the NASA History Division.

Space Shuttle Mission Chronologies: These short mission descriptions provide launch and landing information, a crew list, and mission highlights. They originally existed as individual pages for each Space Shuttle mission available from the main Human Spaceflight Web page at Kennedy Space Center. Half way through preparing this volume, these disappeared from the site and were replaced by very brief mission descriptions with much less information. No link was provided to the new location of the original material. The original individual mission files were combined into two PDF files (up to 1999 and from 2000) and a link to a set of HTML files for each mission and placed at a different location *http://www-paokscnasagov/kscpao/nasafact/pdf/1981-99Volume1pdf; http://www-paokscnasagov/kscpao/nasafact/pdf/Volume2pdf;* and *http://sciencekscnasagov/shuttle/missions/missionshtml.* Most links within the HTML files do not work. This experience is indicative of the difficulties encountered when using the internet for research.

Space Science Project Web Sites: Each NASA project has a Web site of varying levels of detail and quality. Some provide extensive information about the mission and science results while others provide only basic information. Some missions have more than one Web site—one dealing with mission elements and a second dealing primarily with the science. The Web sites for the Hubble Space Telescope are particularly useful. The NASA Web site describes the mission, and the Web site sponsored by the Space Telescope Science Institute provides a great deal of detail concerning the science. Universities that co-sponsor or provide instruments to missions often have their own Web sites.

National Space Science Data Center: While not easy to navigate, the Master Catalog on the NSSDC database often provides the only available source of basic information for each mission. While not lengthy, the pages for each mission supply a basic mission description, orbital information, and a list and description of each instrument often with the names and affiliations of the Principal Investigators.

CHAPTER ONE

INTRODUCTION

CHAPTER ONE
INTRODUCTION

NASA began operating as the nation's civilian space agency in 1958 after passage of the National Aeronautics and Space Act. It succeeded the National Advisory Committee for Aeronautics (NACA). The new organization was charged with preserving the role of the United States "as a leader in aeronautical and space science and technology," expanding our knowledge of Earth's atmosphere and space, and exploring flight both within and outside the atmosphere.

The decade from 1989 to 1998 was extremely productive, as NASA added to its already considerable list of achievements. The decade was marked by assembly of the first orbiting Space Station components, launch of the first two Great Observatories, and an outstanding record of safe and fruitful missions. This volume addresses NASA's activities during the decade in the areas of launch systems, human spaceflight, and space science.

A number of groups influenced NASA's direction. Congress influenced the Agency through authorization and appropriation bills. The Executive Branch articulated the President's views on space exploration and development through the annual budget submission, other legislation, and policy directives. During the administration of President George H. W. Bush, as in the administration of President Ronald Reagan before him, the National Space Council shaped and articulated "national" space policy (as defined by the administration). Chaired by the Vice President, the Council consisted of the heads of all departments or other offices with a programmatic role or concern in federal space activities. In November 1993, President William J. Clinton established the National Science and Technology Council, a cabinet-level council serving as the principal means for the President to coordinate science, space, and technology and coordinate the diverse parts of research and development at the federal level.

In addition, a series of advisory committees, task groups, and commissions, often formed by the NASA Administrator to address specific Agency concerns, advised the Agency on the direction it deemed most advantageous and worthwhile to take and how it could solve identified problems and improve the way "it did business." These advisory committees and commissions typically consisted of individuals, both experts and non-experts in fields related to space, from diverse backgrounds such as industry, academia, the military, Congress, NASA, and other government agencies. Proceedings of these groups, as well as national policy directives, are cited in the following chapters where relevant.

Overview of the Agency

NASA is an independent federal government agency consisting of a headquarters in Washington, DC, nine Centers or installations located around the United States, and the Jet Propulsion Laboratory, a government-owned, contractor-occupied facility in Pasadena, California, operated under contract to NASA and staffed by the California Institute of Technology. NASA Headquarters consists of program and staff offices providing overall program management and administrative functions for the Agency. During the 1990s, the Agency adopted a thematic strategic enterprise approach to supplement its traditional program office structure. These strategic enterprises, led by Associate Administrators, developed strategy and policy, formulated programs, and assigned lead Centers for specific projects and activities. Although the focus and content of the enterprises changed at times, as did their names, they generally fell into the areas of aeronautics, human spaceflight, Earth science, and space science. To provide continuity when dealing with Congress, NASA retained its program office designations for its annual budget submissions to Congress. Table 1–1 shows NASA's program offices and their major functional areas as stated in the annual budget submissions broken down by appropriation.

NASA Centers operated fairly autonomously to implement Agency plans, programs, and activities as part of a program office or strategic enterprise. Each Center focused on particular types of projects, technology, and discipline areas, indicated by its designation as a Center of Excellence (see table 1–2). Installations were assigned the role of Lead Center for programs based on the Center's mission and Center of Excellence capabilities. Each Center was responsible for day-to-day program management and execution, hiring its own personnel, and awarding its own procurements.

Program and Project Development

NASA called most of its activities "programs" or "projects." The Agency defined programs as "major activities within an enterprise that have defined goals, objectives, requirements, and funding levels, and consist of one or more projects." Projects were "significant activities designated by a program and characterized as having defined goals, objectives, requirements, life-cycle costs, a beginning, and an end."[1]

NASA's programs and projects followed a sequence of events, called a life cycle, consisting of program formulation, program implementation, and several approval milestones needing to be passed. For most of the decade, the life cycle consisted of six phases (with corresponding letter designations). Formulation included Advanced Studies (Pre-Phase A), Preliminary Analysis (Phase A), and Definition (Phase B). Program implementation included Design (Phase C), Development (Phase D), and Operations (Phase E).[2]

In 1998, NASA replaced this structure with one consisting of the same two major stages—program formulation and program implementation—neither of these divided into formal phases. Program formulation included program planning, systems analysis, and technology requirements synthesis. Program implementation included program control, technical requirements management, and the design and development of technology and systems. Several reviews and evaluations took place at specific points within each stage.

Typically, funding for project formulation activities came out of research and technology funding held at the Headquarters level. Congressional funding for a specific program was received after a major review was conducted at the end of program implementation. At all stages, a prescribed set of documents, performance metrics, and evaluations were a large part of the process to ensure that requirements were achieved.[3]

NASA's Budget

NASA depends on a reasonable level of funding from Congress each year to finance its programs.[4] The federal budget process is complex and requires foresight and planning by everyone involved with the allocation of resources. This section provides an overview of the budget process. More detailed information can be found in chapter 7 of Volume VIII of the *NASA Historical Data Book, 1989–1998.*

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[1] NASA Procedures and Guidelines (NPG) 7120.5A, "NASA Program and Project Management Processes and Requirements," Effective April 3, 1998 (canceled).

[2] NASA Handbook (NHB) 7120.5, "Management of Major System Programs and Projects Handbook," November 8, 1993 (canceled).

[3] NPG 7120.5A.

[4] The government operates on a "fiscal year" basis that runs from October 1 through September 30 of the following year. The fiscal year is called by the year in which it ends, e.g., FY 1993 runs from October 1, 1992, through September 30, 1993.

Congress funded NASA's activities each year by means of large appropriations categories. Through fiscal year (FY) 1994, four major appropriations funded the Agency. The Research and Development (R&D) appropriation funded most of NASA's programs and projects. Spaceflight, Control, and Data Communications (SFC&DC) funded operation of the Space Shuttle, some Space Station activities, and tracking and data acquisition activities. The Research and Program Management (R&PM) appropriation funded civil service salaries, regardless of the project or office in which an individual worked, as well as related expenses such as benefits, training, and travel. Construction of Facilities (C of F) funded design and construction of facilities, purchase of land, and similar activities. The Office of Inspector General appropriation funded this independent office.

In FY 1995, the appropriations categories changed to a three-appropriation structure. The new categories were Human Space Flight (HSF), Science, Aeronautics, and Technology (SAT), and Mission Support (MS). HSF funded most Space Station and Space Shuttle activities. The SAT appropriation funded most research and development programs with the exception of the Space Station and Space Shuttle. MS funded the civil service workforce, space communication services, safety and quality assurance activities, maintenance, and most activities formerly funded by the C of F appropriation. The Office of Inspector General retained its appropriation arrangement, as it had before.

NASA was required to spend its funds according to the way Congress allocated funds among the appropriation categories. Although a program office could administer activities from more than one appropriation category, the Agency could not transfer funds from one appropriation category to another without congressional notification. Table 1–3 shows the major programs within each appropriation category.

NASA's budget planning cycle lasted two years. Two years before the beginning of a fiscal year, NASA Headquarters sent programmatic and budget guidelines to each Center based on the Agency's long-range plans and budget forecasts from the Office of Management and Budget (OMB). Each Center then prepared a detailed budget, or Program Operating Plan, for the fiscal year beginning two years in the future. The Center also refined the budget for the remainder of the current fiscal year and revised the budget request for the next fiscal year that it had submitted the year before. Additionally, it provided budget figures for future years. Upon approval from each Center's comptroller and Director, this budget was forwarded to the appropriate Headquarters program or enterprise office, the NASA comptroller, and the NASA Administrator. The comptroller and Administrator finalized the budget request and submitted it to the OMB. After OMB review and further discussion with NASA, the OMB formally submitted the NASA budget request to Congress as part of the President's budget request in February of each year.

NASA prepared and submitted a draft authorization bill that went to NASA's House and Senate science committees that authorized NASA's budget. Ideally, each committee held hearings and discussed the bill with the NASA Administrator and heads of specific programs. These program heads often testified before Congress in preparation for a vote on the bill. The final bill was sent to the full House and Senate and, if necessary, a conference committee reconciled any differences between the House and Senate versions. When both houses of Congress passed the same bill, it went to the President for signature. The authorization bill limited how much could be appropriated and could set conditions on how funds were to be spent.

In some years, however, Congress did not pass an authorization bill. In those years, although Congress held authorization hearings and discussions, only an appropriations bill was passed.[5] The appropriations bill was required for NASA to actually spend funds. Without an appropriations bill at the start of a fiscal year, Congress must pass a continuing resolution allowing agencies to continue operating at a particular level of funding.

The appropriation process was similar to the authorization process, with the bills going to the proper appropriations committees for discussion, revision, and approval. However, in practice, appropriations committees usually did not review the proposed budget in as great detail as the authorization committees unless its members were especially interested in a particular program. Upon committee approval, the appropriations bills went to the full House and Senate, back to a conference committee if necessary, and finally to the President. After approval by the President, the OMB established controls on the release of the funds to the Agency.

Once NASA received control over its appropriated funds, it designated the funds for its various programs, projects, and facilities. An "account" for each item was set up allowing the Agency to commit, obligate, cost, and disburse the funds and track them as they were spent.[6] NASA scrupulously monitored all of its financial activities, first at the project and Center level and then at the Headquarters level. Its financial transactions were eventually reviewed by the congressional General Accounting Office to ensure that they were legal and followed appropriate procedures.

In FY 1995, NASA began a "full cost" accounting initiative. This initiative included all costs (both direct and indirect) associated with an activity, not just funds spent during a limited part of a program's life cycle (usually the prelaunch development phase). Before full cost was implemented, expenses associated with launch and mission operations and the cost of civil service salaries were not counted toward project costs but were instead put into a separate "launch support," or "mission operations" category. Full cost included all of these costs such as civil service salaries, the use of facilities, and support services associated with the benefiting activities as part of a project's expenses, thus providing a more accurate picture of the actual cost of a project. Formulating a full cost budget allowed for full disclosure of NASA's activities and established a more defined link between funds received and funds spent. Full cost also provided the Agency with greater accountability regarding the use of its resources. For FY 1997 and FY 1998, NASA prepared dual budgets: one using full cost and one using traditional budget methods. In the next decade, NASA went completely to using full cost.

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[5] An authorization bill is not required for appropriations to be passed.

[6] "To cost" funds refers to the process of recording the total value of resources used in producing goods or rendering services.

The budget tables in the following chapters show the initial amounts requested by NASA each fiscal year (two years before the start of the fiscal year for which the funds were requested) and the revised amounts (one year before the start of the fiscal year for which the funds were requested). The tables also show the programmed amount, or what the program actually had available to spend. If full cost figures are available for an activity, they are shown.

This volume addresses NASA's launch systems, human spaceflight, and space science activities. Each chapter provides a review of activities of the previous decade, an overview of the topic, budget and funding data, management structure and personnel, and a description of the systems and missions of the decade.

Table 1–1. Programs Within the R&D Appropriation

1989	1990	1991	1992	1993
Office of Space Flight • Space Transportation Capability Development				
Office of Space Station • Space Station	Office of Space Flight • Space Station			
Office of Space Science and Applications • Physics and Astronomy • Planetary Exploration • Life Sciences • Solid Earth Observations • Environmental Observations • Materials Processing in Space • Communications • Information Systems	Office of Space Science and Applications • Physics and Astronomy • Planetary Exploration • Life Sciences • Earth Sciences • Materials Processing in Space • Communications • Information Systems			
Office of Commercial Programs • Technology Utilization • Commercial Use of Space				

Table 1–1. Programs Within the R&D Appropriation (Continued)

1989	**1990**	**1991**	**1992**	**1993**
Office of Aeronautics and Space Technology • Aeronautical Research and Technology • Transatmospheric Research and Technology • Space Research and Technology		Office of Aeronautics and Space Technology • Aeronautical Research and Technology • Transatmospheric Research and Technology • Space Research and Technology • Exploration Mission Studies	Office of Aeronautics and Space Technology • Aeronautical Research and Technology • Transatmospheric Research and Technology • Space Research and Technology	
				Office of Space Exploration
Office of Safety, Reliability, Maintainability, and Quality Assurance • Safety, Reliability, and Quality Assurance				
Office of Space Tracking and Data Systems • Advanced Systems				
	University Space Science and Technology Academic Programs Technology Academic Programs	Academic Programs		

Table 1–2. Centers of Excellence

Center	Designated Center of Excellence	Mission Area
Ames Research Center	Information technology	Aviation operations systems and astrobiology
Dryden Flight Research Center	Atmospheric flight operations	Flight research
Goddard Space Flight Center	Scientific research	Earth science and physics and astronomy
Jet Propulsion Laboratory	Deep space systems	Planetary science and exploration
Johnson Space Center	Human operations in space	Human exploration and astro materials
Kennedy Space Center	Launch and cargo processing systems	Space launch
Langley Research Center	Structure and materials	Airframe systems and atmospheric science
Lewis Research Center	Turbomachinery	Aeropropulsion
Marshall Space Flight Center	Space propulsion	Transportation systems development and microgravity
Stennis Space Center	Propulsion testing systems	Propulsion test

Table 1–3. Program Office Functional Areas

Programs Within the R&D/Science, Aeronautics and Technology Appropriation				
1994	**1995**	**1996**	**1997**	**1998**
Office of Space Flight • Space Transportation Capability Development	Moved to Human Space Flight appropriation			
Office of Space Systems Development • Space Station	Moved to Human Space Flight appropriation			
Office of Space Science • Physics and Astronomy • Planetary Exploration			Office of Space Science (separate mission divisions were dropped)	
Office of Life & Microgravity Sciences & Applications • Life Sciences • Microgravity Science Research • Shuttle/Spacelab Payload, Mission Management and Integration	Office of Life & Microgravity Sciences & Applications • Life Sciences • Microgravity Science Research • Space Shuttle/ Spacelab Payload, Mission Management and Integration • Space Station Payload Facilities	Office of Life & Microgravity Sciences & Applications • Life Sciences • Microgravity Science Research • Space Shuttle/Spacelab Payload, Mission Management and Integration • Space Station Payload Facilities • Aerospace Medicine/ Occupational Health		Office of Life & Microgravity Sciences & Applications • Life Sciences • Microgravity Science Research • Space Shuttle/ Spacelab Payload, Mission Management and Integration • Aerospace Medicine/ Occupational Health • Space Product Development

Table 1–3. Program Office Functional Areas (Continued)

Programs Within the R&D/Science, Aeronautics and Technology Appropriation (Continued)				
1994	**1995**	**1996**	**1997**	**1998**
Office of Mission to Planet Earth				
Office of Advanced Concepts & Technology • Space Research and Technology • Commercial Programs • Technology Transfer • Commercial Use of Space	Office of Advanced Concepts & Technology • Advanced Concepts and Technology (combined functional areas)	Reallocated to Space Access and Technology and other programs		
		Office of Space Access and Technology • Space Access and Technology		Program office dissolved; activities moved to Aeronautics and Space Transportation Technology
	Launch Services	Included with Space Access and Technology		Moved to Human Space Flight appropriation

Table 1–3. Program Office Functional Areas (Continued)

Programs Within the R&D/Science, Aeronautics and Technology Appropriation (Continued)				
1994	**1995**	**1996**	**1997**	**1998**
Office of Aeronautics • Aeronautical Research & Technology • Transatmospheric Research & Technology	Office of Aeronautics • Aeronautical Research & Technology		Office of Aeronautical Research and Technology • Research and Technology Base • Focused Programs	Office of Aeronautics and Space Transportation Technology • Aeronautical Research and Technology • Commercial Technology/SBIR • Advanced Space Transportation Technology
Safety, Reliability, and Quality Assurance • Safety, Reliability, and Quality Assurance	Moved to Mission Support appropriation			
Space Communications • Advanced Systems	Mission Communication Services • Ground Network • Mission Control & Data Systems • Space Network Customer Service			
Academic Programs	Academic Programs • Education • Minority University Research and Education			

Table 1–3. Program Office Functional Areas (Continued)

Programs Within the Spaceflight, Control, and Data Communications Appropriation					
1989	**1990**	**1991**	**1992**	**1993**	**1994**
Office of Space Flight • Shuttle Production and Operational Capability • Space Transportation Operations					Space Flight • Shuttle Production and Operational Capability • Space Transportation Operations • Launch Services
Office of Space Tracking and Data Systems • Space and Ground Network, Communications and Data Systems					
Space Station					
U.S.-Russian Cooperative Program					
Space Shuttle					
Payload & Utilization Operations					

USA
NASA
Discovery

CHAPTER TWO

LAUNCH SYSTEMS

CHAPTER TWO
LAUNCH SYSTEMS

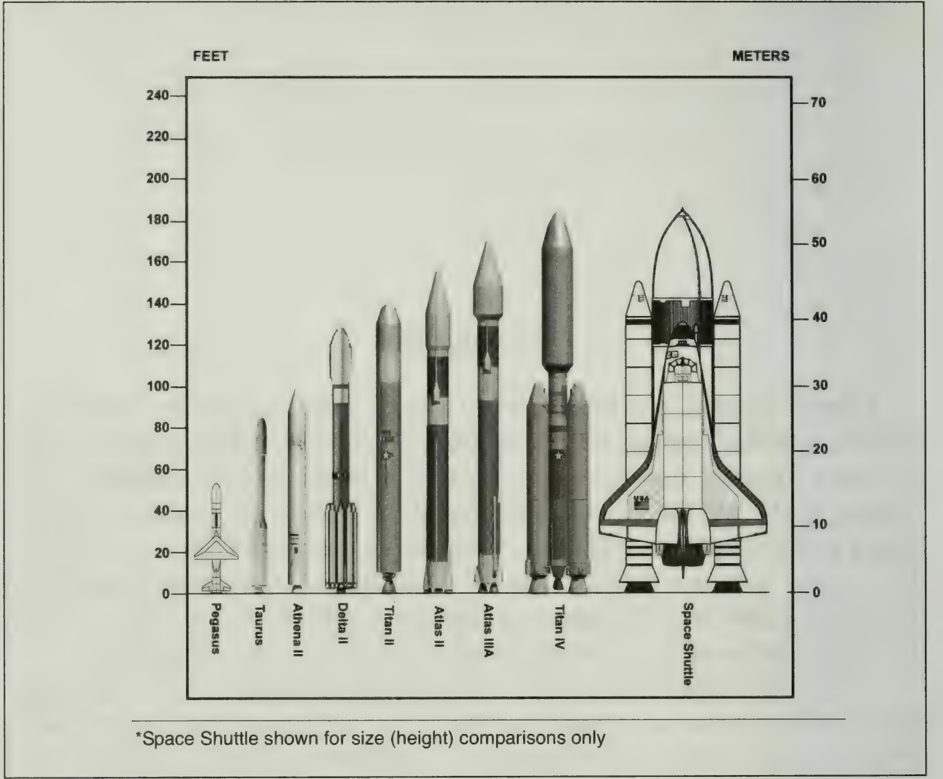
Introduction

Launch systems provide access to space, necessary for the majority of NASA's activities. During the decade from 1989–1998, NASA used two types of launch systems, one consisting of several families of expendable launch vehicles (ELV) and the second consisting of the world's only partially reusable launch system—the Space Shuttle. A significant challenge NASA faced during the decade was the development of technologies needed to design and implement a new reusable launch system that would prove less expensive than the Shuttle. Although some attempts seemed promising, none succeeded.

This chapter addresses most subjects relating to access to space and space transportation. It discusses and describes ELVs, the Space Shuttle in its launch vehicle function, and NASA's attempts to develop new launch systems. Tables relating to each launch vehicle's characteristics are included. The other functions of the Space Shuttle—as a scientific laboratory, staging area for repair missions, and a prime element of the Space Station program—are discussed in the next chapter, Human Spaceflight. This chapter also provides a brief review of launch systems in the past decade, an overview of policy relating to launch systems, a summary of the management of NASA's launch systems programs, and tables of funding data.

The Last Decade Reviewed (1979–1988)

From 1979 through 1988, NASA used families of ELVs that had seen service during the previous decade. NASA also introduced new models of ELVs and began using the fleet of Space Shuttles to launch satellites into space. NASA used three families of ELVs: the Scout, Delta, and Atlas. These ELVs were increasingly acquired from the private sector and were used to send commercial as well as scientific and other research satellites into space in compliance with national space policy. The success rate for ELV launches was high during this decade; there were only three ELV launch failures: 1984, 1986, and 1987.


FEET
METERS
240
220
200
180
160
140
120
100
80
60
40
20
0
70
60
50
40
30
20
10
0
Pegasus
Taurus
Athena II
Delta II
Titan II
Atlas II
Atlas IIIA
Titan IV
Space Shuttle

*Space Shuttle shown for size (height) comparisons only

Figure 2–1. NASA's Fleet of Launch Vehicles (1989–1998). Not Pictured: the Scout and the Conestoga. The Scout stood 75 feet (23 meters) tall, placing it between the Pegasus and Taurus. The Conestoga stood 50 feet (14 meters), making it about the same height as the standard Pegasus.

This decade marked the Space Shuttle's debut as the world's first Reusable Launch Vehicle (RLV). The Space Shuttle fleet consisted of four orbiters: the *Columbia*, *Challenger*, *Discovery*, and *Atlantis*. An earlier orbiter, the *Enterprise*, was used as a test vehicle before the Space Transportation System's first spaceflight in 1981, but it did not fly in space.

The Space Shuttle flew 26 successful missions before January 28, 1986, when the *Challenger* exploded only a few seconds into flight, taking the lives of its crew. This single tragedy defined the decade and greatly obscured the program's achievements. It would be more than two years before the Space Shuttle returned to flight in 1988.

Government policy had initially stated its intention to replace ELVs with the Shuttle as the country's prime launch vehicle. However, as early as 1984, Congress had expressed reservations about relying solely on the Shuttle. During the two years following the *Challenger* accident, NASA used ELVs exclusively to launch the Nation's satellites. When Shuttle flights resumed in 1988, NASA implemented a "mixed fleet strategy." This strategy reserved the Shuttle for those flights requiring a human presence or where only the Shuttle could handle the payloads.

Overview of NASA's Launch Systems (1989–1998)

During 1989–1998, 281 U.S. launches occurred. Of these, 215 were ELV launches, and 66 were Space Shuttle missions.[1] Twenty-seven Shuttle missions did not deploy a payload, and several other Shuttle missions were used to deploy and quickly retrieve payloads sent into space to conduct experiments. All Shuttle and most ELV launches took place from Cape Canaveral, Florida. Polar missions usually launched from Vandenberg Air Force Base, California. ELV launches took place using Athena; Atlas; Conestoga; Delta; Pegasus; Scout; Taurus; and Titan launch vehicles. The Conestoga launch took place from Wallops Flight Facility on the Eastern Shore of Virginia. Figure 2–1 shows NASA's launch vehicles.

A wide range of payload types was launched. Most were either commercial or DOD payloads and had communications or navigation purposes, although some were reconnaissance satellites. Some of the launches carried satellites for other countries, among them Japan, the Philippines, the United Kingdom, Spain, India, Korea, Canada, and various international groups of satellite owners. A smaller number of launches deployed scientific satellites; these were usually NASA missions. The success rate for all types of launches during this decade was very high. All Shuttle launches succeeded. For ELVs, the total success rate was almost 94 percent.

National space policy and legislation, either in place by 1989 or promulgated during the decade, greatly determined the direction of space launch development and activities. During the administration of President George H. W. Bush, and with Vice President Dan Quayle's special interest in space policy, NASA and other agencies and organizations undertook a large number of space transportation studies. These studies grew partly out of Congress's desire to reduce the federal budget and, in particular, NASA's budget, and partly out of the view that new launch technologies were needed.[2] These studies, and the policies and legislation reflecting them, had three primary themes: a new heavy launch system was needed to augment or replace the Shuttle; an RLV needed to be developed; and ELV launches and launch services should largely be commercial enterprises.[3]

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[1] One joint U.S.-French launch took place from an Ariane launch vehicle.

[2] Andrew Butrica, "X-33 Fact Sheet #1, Part I: The Policy Origins of the X-33," *The X-33 History Project Home Page* (December 7, 1997), *http://www.hq.nasa.gov/office/pao/History/x-33/facts_1.htm* (accessed February 29, 2005).

[3] Advisory Committee on the Future of the U.S. Space Program, "Report of the Advisory Committee on the Future of the U.S. Space Program," December 17, 1990, *http://www.hq.nasa.gov/office/pao/History/augustine/racfup1.htm* (accessed March 14, 2005).

Executive policy statements and legislation emphasized the role of the private sector. Legislation took the government out of the business of building ELVs and supplying launch services for its primary payloads and required NASA to purchase them from commercial providers whenever possible. Policy and legislation directed the government to make national launch facilities available for private use and encouraged development of new launch systems by the private sector.[4] National policy also emphasized the importance of having a resilient and balanced launch capability so launch operations could continue even if any one system failed.

Further, restating policy set forth during President Ronald Reagan's administration,[5] Bush's policy dictated that the Shuttle would be reserved for launches requiring a human presence or the special capabilities of the Shuttle. It also stated that U.S. payloads must be launched from U.S. launch vehicles unless excepted by the President or a person designated by the President.[6]

In January 1993, William J. Clinton became President. In January 1994, the NASA Office of Space Systems Development released a study titled "Access to Space," undertaken in response to a congressional request in the NASA FY 1993 Appropriations Act. The goal of this study was to identify alternative approaches to space access that would reduce the cost of space transportation and increase safety for flight crews. The study concluded that the best option was "to develop and deploy a fully reusable single-stage-to-orbit pure-rocket launch vehicle fleet incorporating advanced technologies" and to phase out current systems "beginning in the 2008 time period."[7]

On August 5, 1994, President Clinton released a National Space Transportation Policy splitting the responsibility for space transportation between DOD and NASA. The policy gave DOD lead responsibility for improving ELVs and NASA lead responsibility for upgrading the Space Shuttle and developing and demonstrating new RLVs to replace the Space Shuttle.[8] In response, DOD initiated the Evolved Expendable Launch Vehicle program, and NASA initiated the RLV program to develop and flight-test experimental RLVs.

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[4] A *Bill to Facilitate Commercial Access to Space, and for Other Purposes,* 100th Congress, 2nd sess., H.R. 4399, (October 14, 1988); National Space Policy Directive, NSPD-1,"National Space Policy Directives and Executive Charter," November 2, 1989, *http://www.fas.org/spp/military/docops/national/nspd1.htm* (accessed March 1, 2005); NSPD-3, "U.S. Commercial Space Policy Guidelines," February 11, 1991, *http://www.fas.org/spp/military/docops/national/nspd3.htm* (accessed March 1, 2005).

[5] The White House Office of the Press Secretary, "Presidential Directive on National Space Policy," *Aeronautics and Space Report of the President, 1998 Activities* (Washington, DC: National Aeronautics and Space Administration, 1990), p. 190.

[6] National Space Policy Directive, NSPD-2, "Commercial Space Launch Policy," September 5, 1990, *http://www.hq.nasa.gov/office/codez/new/policy/pddnspd2.html* (accessed March 1, 2005).

[7] Office of Space Systems Development, NASA Headquarters, "Access to Space Study, Summary Report," January 1994, p. i (NASA History Office file 009830).

[8] The White House, Office of Science and Technology Policy, Presidential Decision Directive (PDD), National Science and Technology Council-4 (NSTC), *National Space Transportation Policy* (August 5, 1994), *http://www.au.af.mil/au/awc/awcgate/nstc4.htm* (accessed February 28, 2005).

Clinton's policy also set guidelines for the use of foreign launch systems and components and excess ballistic missile assets for space launches. His policy also encouraged an expanded private sector role in space transportation research and development.

In September 1996, the White House released a National Space Policy stating that NASA would work with the private sector to develop flight demonstrators to make a decision about the development of a new reusable launch system. The policy also stated that NASA would acquire launch vehicles from the private sector unless the Agency's special technical abilities were needed.[9] Legislation passed in 1998 stated that the federal government would acquire space transportation services from commercial providers, except when there was a reason to use the Space Shuttle or because it was not cost effective or in the best interests of the mission. The legislation also allowed the Federal Aviation Administration (FAA) to license firms to fly vehicles back from space. Since the 1980s, private firms had been able to acquire licenses for commercial space launches; but the licenses had not provided for return from space, which had been too expensive for all but government agencies. This bill also obligated NASA's Administrator to prepare for transferring operation and management of the Space Shuttle to the private sector.[10]

Management of NASA's Launch Systems

In the decade from 1989 through 1998, NASA's launch systems included both ELVs and the Space Shuttle. NASA's launch system programs also focused on developing new ways to provide access to space by using RLVs and other advanced technologies. As in the past, the offices managing these various activities frequently shifted among organizations as NASA reorganized in an effort to more efficiently achieve its objectives. At times, management of ELVs, the Space Shuttle, and developing launch programs were all in the same organization. At other times, they were spread among different areas of the Agency.[11] For part of NASA's fourth decade, management of NASA's expendable launch systems remained with the Office of Space Flight (Code M), although it did not receive the prominence it had in past decades because providing ELV services became more of a commercial function. Management of Space Shuttle activities always remained in the Office of Space Flight.

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[9] The White House National Science and Technology Council, "Fact Sheet–National Space Policy," PDD-NSTC-8 (September 19, 1996), *http://www.fas.org/spp/military/docops/national/nstc-8.htm* (accessed March 15, 2005).

[10] *Commercial Space Act of 1998,* 105th Congress., 1st sess., Public Law 105-303, Title II, (October 28, 1998).

[11] NASA assigned letters (called codes) as a quick way to refer to its top-level offices. The offices and codes applicable to launch systems during this decade were:
- Office of Space Flight–Code M
- Office of Space Systems Development–Code D
- Office of Advanced Concepts and Technology–Code C
- Office of Space Access and Technology–Code X
- Office of Space Science and Applications–Code E, later changed to Code S

Development programs were frequently located in other organizations. The sections that follow correspond to the major reorganizations and changes in the management structure of NASA's launch systems activities.

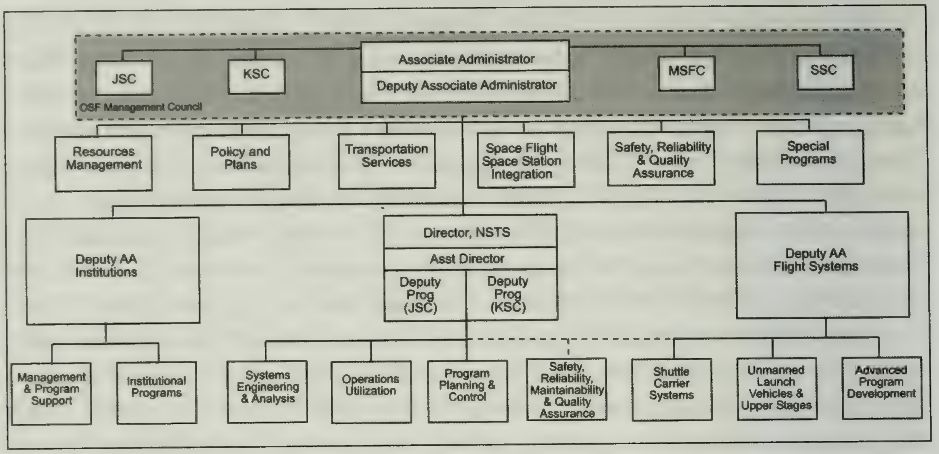
Associate Administrator
Deputy Associate Administrator
JSC
KSC
MSFC
SSC
OSF Management Council
Resources Management
Policy and Plans
Transportation Services
Space Flight Space Station Integration
Safety, Reliability & Quality Assurance
Special Programs
Deputy AA Institutions
Director, NSTS
Asst Director
Deputy Prog (JSC)
Deputy Prog (KSC)
Deputy AA Flight Systems
Management & Program Support
Institutional Programs
Systems Engineering & Analysis
Operations Utilization
Program Planning & Control
Safety, Reliability, Maintainability & Quality Assurance
Shuttle Carrier Systems
Unmanned Launch Vehicles & Upper Stages
Advanced Program Development

Figure 2–2. Office of Space Flight (Code M), February 1989.

Phase I: 1989–1990

The year 1989 and the first part of the 1990s saw three rapid reorganizations of the Office of Space Flight and changes in its leadership. In February 1989, the Office of Space Flight, led by Admiral Richard Truly, reorganized from its post-*Challenger* structure into an office consisting of three major divisions: 1) Institutions, headed by Richard J. Wisniewski; 2) Flight Systems, led by Joseph B. Mahon, and 3) the National Space Transportation System program (soon renamed the Space Shuttle program), headed by Arnold D. Aldrich (see Figure 2–2). Charles R. Gunn led the Unmanned Launch Vehicles and Upper Stages office in the Flight Systems Division. Aldrich left his post as head of the Shuttle program in October 1989 to become Associate Administrator of the Office of Aeronautics, Exploration and Technology and was replaced by Capt. Robert L. Crippen, initially as acting Director of the Space Shuttle program and as Director from February 1990.

Dr. William B. Lenoir, a former Space Shuttle astronaut, became Associate Administrator of the Office of Space Flight in July 1989, leaving his position as head of the Office of Space Station, a position he had held only since May 1989. In May, he had also been asked by Truly to develop a plan for consolidating the Offices of Space Flight and Space Station.[12] When President George H. W. Bush named Truly NASA Administrator, Lenoir took over leadership of the Office of Space Flight.

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[12] "Space Station Program Leadership Selected by Truly," *NASA News* Release 98-77, May 19, 1989. (NASA History Office Folder 009610).

The February 1989 structure lasted less than a year because the office reorganized again in December and then made another small change in March 1990. The December 1989 reorganization consolidated the Office of Space Flight and Office of Space Station into a single organization consisting of four divisions that retained the name the Office of Space Flight (see Figure 2-3). Richard H. Kohrs took over the leadership of Space Station *Freedom*; Crippen, Wisniewski, and Mahon continued to head the Space Shuttle, Institutions, and Flight Systems divisions, respectively. Gunn continued as Director of Unmanned Launch Vehicles and Upper Stages. The March 1990 reorganization added a second Deputy Associate Administrator to the Office of Space Flight. In late 1990, Mahon was replaced by Michael T. Lyons as head of Flight Systems, and I. Duke Stanford became head of Institutions when Wisniewski retired from NASA. Around the same time, the heads of the divisions assumed the title of Deputy Associate Administrator of their respective organizations.

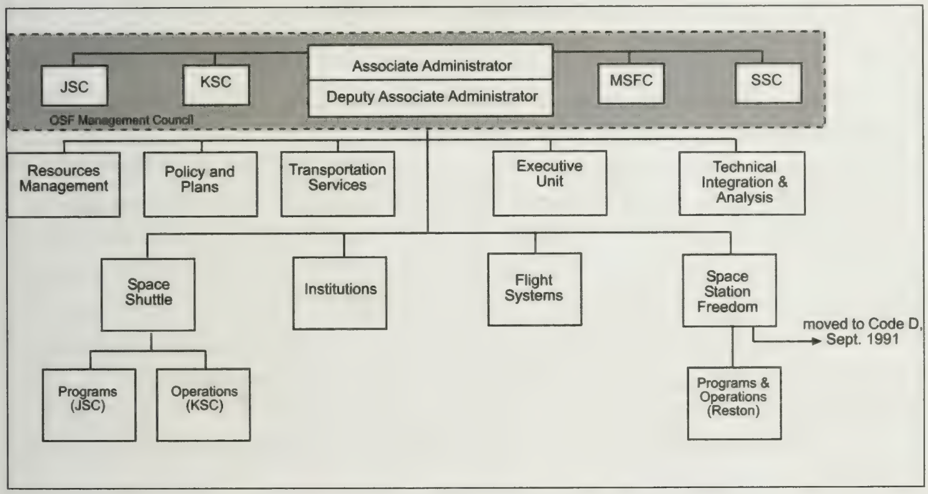
JSC
KSC
Associate Administrator
Deputy Associate Administrator
MSFC
SSC
OSF Management Council
Resources Management
Policy and Plans
Transportation Services
Executive Unit
Technical Integration & Analysis
Space Shuttle
Institutions
Flight Systems
Space Station Freedom
moved to Code D, Sept. 1991
Programs (JSC)
Operations (KSC)
Programs & Operations (Reston)

Figure 2–3. Office of Space Flight, December 1989.

Phase II: 1991–1992

The 1989 organizations remained in place until September 1991, when Administrator Truly followed the guidance of the Advisory Committee on the Future of the U.S. Space Program of December 1990, headed by Norman R. Augustine, and created a new Office of Space Systems Development (Code D).[13]

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[13] NASA press release for September 13, 1991, that announced the formation of the new office referred to it as the Office of Space Flight Development; "New Office of Space Flight Development Announced," *NASA News* Release 91-148, September 13, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-148.txt* (accessed March 2, 2005). Beginning with an October 3, 1991, press release, the office was referred to as the Office of Space Systems Development." "NASA Administrator Announces Key Appointments," *NASA News* Release 91-161, October 3, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-161.txt* (accessed March 2, 2005). This name also appears on the NASA organization chart dated October 20, 1991, and in future references.

This reorganization moved several organizations from the Office of Space Flight to the new organization (see Figure 2–4). This new Space Systems Development office was responsible for Space Station *Freedom* development; large propulsion systems development, including the new National Launch System and its new space transportation main engine; other large spaceflight development; and the advanced transportation systems program planning function. Aldrich left the Office of Aeronautics, Exploration and Technology to lead the new Space Systems Development office. Dr. C. Howard Robins, Jr. was named Deputy Associate Administrator for the new office in October. The Flight Systems Division moved to the Office of Space Systems Development, with Lyons as its head. Kohrs was named head of the Space Station Freedom Division.

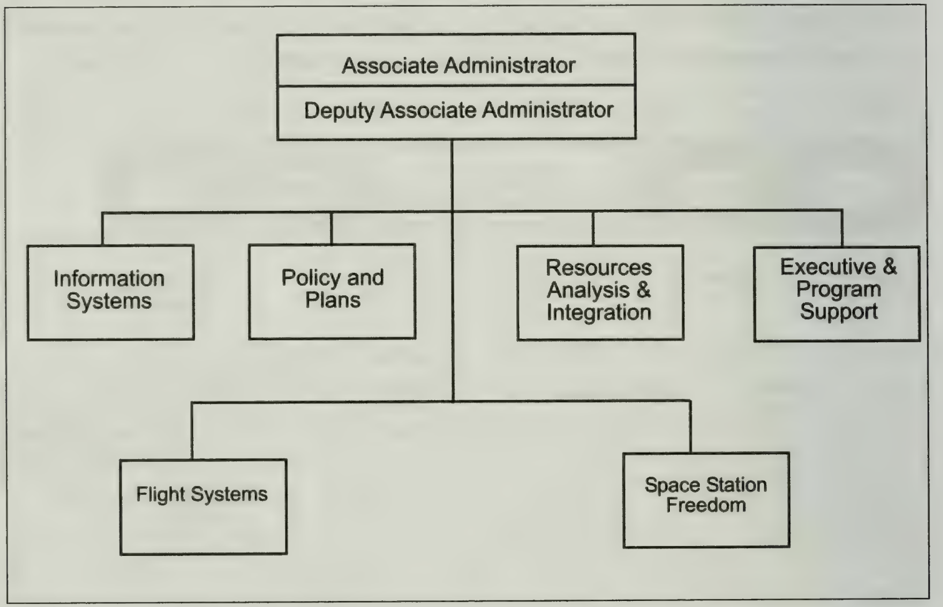
Associate Administrator
Deputy Associate Administrator
Information Systems
Policy and Plans
Resources Analysis & Integration
Executive & Program Support
Flight Systems
Space Station Freedom

Figure 2–4. Office of Space Systems Development (Code D).

The scaled-down Office of Space Flight continued to focus on Space Shuttle operations and also retained responsibility for Space Station *Freedom/* Spacelab operations and utilization, ELV operations, and upper stages.[14] In December, Leonard S. Nicholson was named Director of the Space Shuttle program in the Office of Space Flight, replacing Crippen, who became Director of Kennedy Space Center. Lenoir remained as Associate Administrator of the Office of Space Flight until May 1992, when he resigned his leadership post and left NASA.

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[14] "New Office of Space Flight Development Announced," *NASA New,* Release 91-148, September 13, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-148.txt* (accessed March 1, 2005).

In April 1992, Daniel S. Goldin replaced Truly and became NASA's new Administrator. Among his first hiring decisions was the appointment of Maj. Gen. Jeremiah W. Pearson, III as Associate Administrator of the Office of Space Flight. Bryan D. O'Connor, a former NASA astronaut, was named Deputy Associate Administrator for programs within the Office of Space Flight. In June, Pearson named Thomas Utsman, who had been serving as Deputy Associate Administrator for the Office of Space Flight since June 1990, as Program Director for the Space Shuttle. In March 1993, Pearson named Brewster Shaw, Deputy Director of Space Shuttle Operations, to the position of Space Shuttle Program Manager, replacing Nicholson, who left to take the position of acting Director of Engineering at Johnson Space Center.

In the summer of 1992, management of ELVs and upper stages, still under the leadership of Gunn, moved to the Office of Space Science and Applications (OSSA) Launch Vehicles Office. This was done largely because ELVs launched space and Earth science missions, and it seemed more efficient for all aspects of these missions to be in the same organization. The Launch Vehicles Office was responsible for managing the ELV and upper stages launch services program. It maintained the NASA ELV manifest and served as the primary interface with the U.S. Air Force, foreign governments, and the ELV industry.[15]

In November 1992, NASA moved the Space Technology program, led by Gregory Reck, out of the Office of Aeronautics and Space Technology (Code R) and merged it with the Office of Commercial Programs (Code C), creating a reformulated Code C, the Office of Advanced Concepts and Technology, under Reck's leadership (see Figure 2–5). The Transportation Division within the new Code C, led by Earl VanLandingham, included several space transportation technology efforts, among them the Solid Propulsion Integrity Program (SPIP), the Advanced Launch Technology effort, and Advanced Programs.[16]

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[15] NASA *Management Instruction* (NMI) 1102.1H, "Role and Responsibilities—Associate Administrator for Space Science and Applications," July 30, 1992; NASA Management Instruction 1102.1I, "Role and Responsibilities—Associate Administrator for Space Science and Applications," June 28, 1993; "Goldin Announces Changes in NASA Organization To Focus and Strengthen Programs and Management," *NASA News* Release 92-172, October 15, 1992, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1992/92-172.txt* (accessed March 2, 2005).

[16] "General Statement," *National Aeronautics and Space Administration, Fiscal Year 1995 Budget Estimates*, p. AS-9.

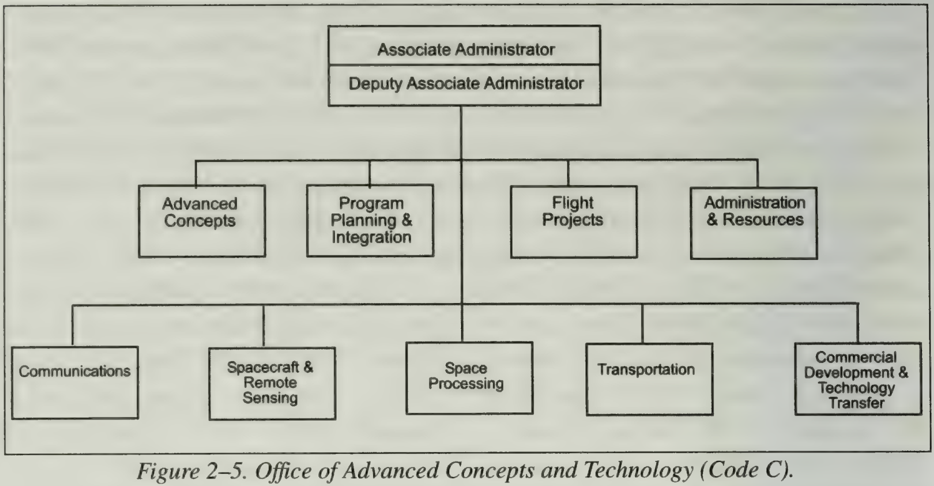
Associate Administrator
Deputy Associate Administrator
Advanced Concepts
Program Planning & Integration
Flight Projects
Administration & Resources
Communications
Spacecraft & Remote Sensing
Space Processing
Transportation
Commercial Development & Technology Transfer

Figure 2–5. Office of Advanced Concepts and Technology (Code C).

Phase III: 1993–1996

In October 1993, Administrator Goldin announced that the Office of Space Flight would again assume responsibility for managing the Space Station Program because Space Shuttle flight activities were becoming increasingly more involved with Space Station planning.[17] This change moved the Space Station out of the Office of Space Systems Development, leaving that office without a major program to manage. O'Connor, Director of the Space Station transition since July 1993, became acting Space Station Program Director, replacing current Program Director Richard Kohrs, who retired in September 1993.[18] O'Connor remained in the position until January 1994, when Wilbur C. Trafton accepted the position.

Further changes in the Office of Space Flight took place in spring of 1994. Utsman left the position of Deputy Associate Administrator for Space Shuttle to return to Kennedy Space Center and become special assistant to the Associate Administrator in the Office of Space Flight. O'Connor, the Office of Space Flight Deputy Associate Administrator, replaced Utsman and also became the Space Shuttle Program Director, responsible for managing the Space Shuttle program. Wisniewski, who retired from NASA in 1990, returned to NASA and replaced O'Connor as Deputy Associate Administrator in the Office of Space Flight. He was responsible for resources, policy and plans, human resources, and management of the human spaceflight installations: Kennedy Space Center, Johnson Space Center, Marshall Space Flight Center, and Stennis Space Center.[19]

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[17] "Goldin Announces Key Space Station Management Moves," *NASA New,* Release 93-191, October 20, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-191.txt* (accessed March 1, 2005).

[18] See chapter 3, Human Spaceflight, for a description of space station transition to Johnson Space Center.

[19] "NASA Announces Space Flight Personnel Changes," *NASA News* Release 94-66, April 28, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-066.txt* (accessed March 1, 2005).

A reorganization in September 1994 consolidated the Advanced Concepts and Technology Office (Code C) and Office of Space Systems Development (Code D) into a new Office of Space Access and Technology (Code X), headed by John E. Mansfield. The divisions within Code X and their heads were: Flight Integration, Jack Levine; Advanced Concepts, Ivan Bekey; Launch Vehicles, Charles Gunn; Commercial Development, Robert Norwood; Space Systems, Samuel Venneri; Space Processing, Edward Gabris; Space Transportation, Col. Gary Payton; and Management Operations, Martin Stein (see Figure 2–6).

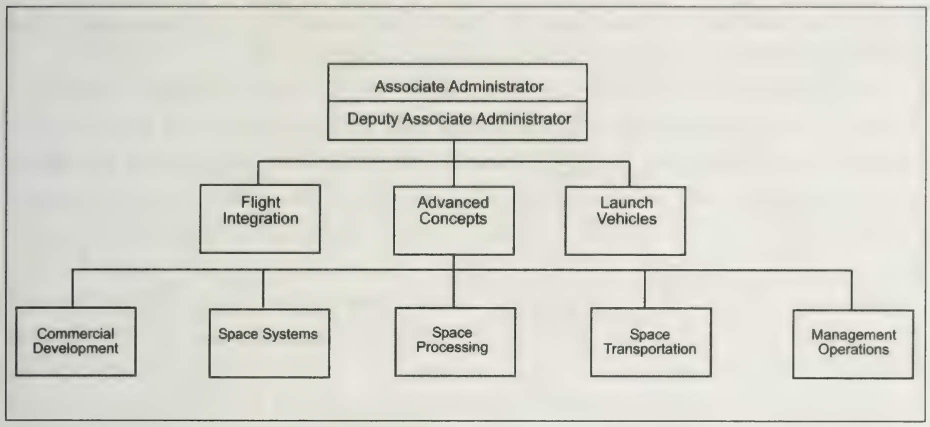

Figure 2–6. Office of Space Access and Technology (Code X), September 1994.

The Space Transportation organization in Code X managed transportation technology, advanced technology development for ELVs and the Space Shuttle, and NASA's efforts to develop an RLV. It also functioned as the single interface with DOD and other outside interests.[20] The Launch Vehicles Office consolidated NASA, the National Oceanic and Atmospheric Administration (NOAA), and international cooperative ELV mission requirements. Management and acquisition of launch services moved from the Office of Space Science and Applications to the Launch Vehicles Office as did acquisition of upper stages. Administration, procurement, and technical oversight of launch service delivery in the small and medium performance classes (Atlas E, Titan II, Pegasus, and Delta II) were handled by Goddard Space Flight Center. Launch services for the intermediate and large performance classes (Atlas I/IIAS and Titan IV/Centaur) were managed by Lewis Research Center. Kennedy Space Center had responsibility for technical oversight of vehicle assembly and testing at the launch site and for launch site spacecraft processing. Marshall Space Flight Center was responsible for managing upper stage missions.[21]

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[20] "NASA Space Access and Technology Office Functions," *Aerospace Daily* (September 26, 1994): 480.

[21] "Office of Space Access and Technology," *National Aeronautics and Space Administration Fiscal Year 1996 Estimates*, pp. SAT 5–37.

In November 1994, Pearson resigned as Associate Administrator of the Office of Space Flight. He was replaced by NASA Chief Engineer and veteran manager Dr. Wayne Littles, who continued a review of the Shuttle work force begun by Pearson a few months earlier. At Administrator Goldin's direction, Littles was looking for any "unnecessary requirements" in the Shuttle program that could be cut and "to make sure that recent budget cuts have not affected safety."[22]

When Gunn retired in the spring of 1995, Charles J. Arcilesi took over as acting head of the Launch Vehicles Office. By summer, the Launch Vehicles Office had moved to the Office of Space Flight, and Karen Poniatowski was appointed to head the Expendable Launch Vehicles Office.

Later in the year, in October 1995, the Office of Space Flight reorganized with the goal of increasing efficiency and reducing the number of people in the organization (see Figure 2–7). In January 1996, Trafton, Director of the Space Station program, assumed additional responsibilities as the acting Associate Administrator for the Office of Space Flight, replacing Littles, who became Director of Marshall Space Flight Center. Trafton was formally named to the position in March. The position also placed Trafton in charge of the Human Exploration and Development of Space (HEDS) Enterprise, one of NASA's four Strategic Enterprises, whose mission was to "open the space frontier by exploring, using, and developing space; and to expand the human experience into the far reaches of the universe."[23] Andrew Allen became acting head of the Space Station program until Gretchen McClain took over in January 1997. In January 1996, the decision was made to transfer the ELV program from the Office of Space Access and Technology (Code X) back to the Office of Space Flight (Code M). In February 1996, O'Connor left his position of Space Shuttle Director, which he held since 1994.

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[22] Ben Iannotta, "Littles Takes Over Space Flight Post as Pearson Quits," *Space News* (November 21–December 4, 1994): 29.

[23] Sharon M. Wong, "Strategic Management: Opening the Space Frontier," *NASA HQ Bulletin* (April 15, 1996): 5.

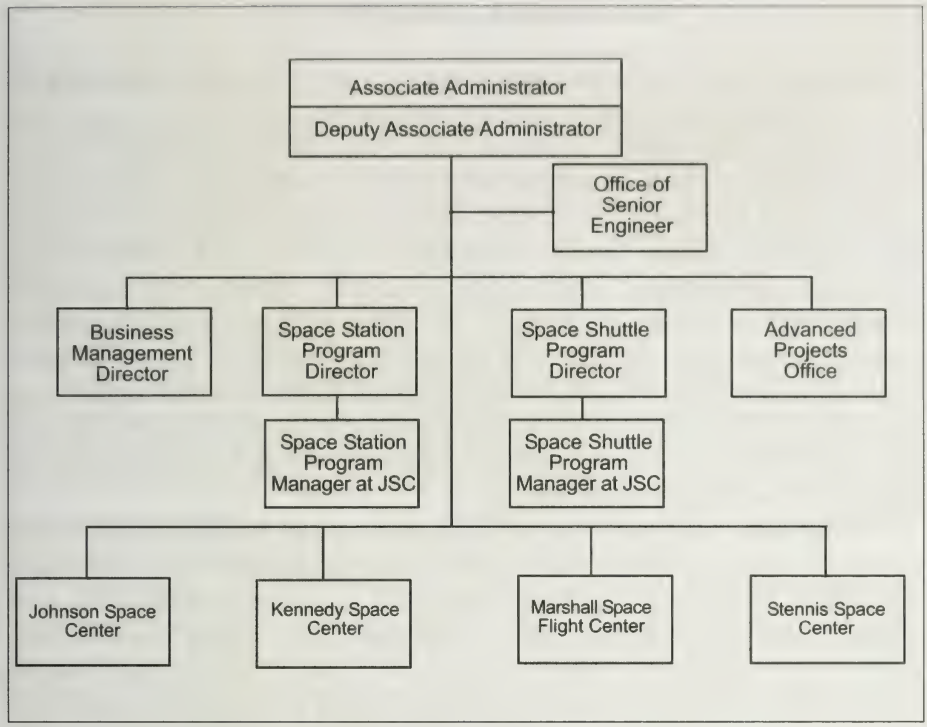
Associate Administrator
Deputy Associate Administrator
Office of Senior Engineer
Business Management Director
Space Station Program Director
Space Shuttle Program Director
Advanced Projects Office
Space Station Program Manager at JSC
Space Shuttle Program Manager at JSC
Johnson Space Center
Kennedy Space Center
Marshall Space Flight Center
Stennis Space Center

Figure 2–7. Office of Space Flight, October 1995.

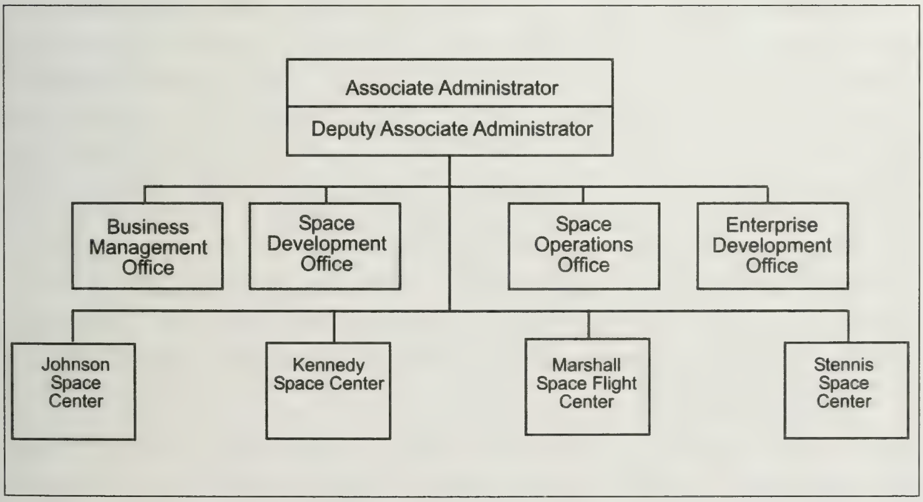
Associate Administrator
Deputy Associate Administrator
Business Management Office
Space Development Office
Space Operations Office
Enterprise Development Office
Johnson Space Center
Kennedy Space Center
Marshall Space Flight Center
Stennis Space Center

Figure 2–8. Office of Space Flight, July 1998.

Phase IV: 1996–1998

In April 1996, NASA announced plans to accelerate the downsizing of NASA Headquarters. Agency officials had previously identified more than 200 positions that could be moved from Headquarters to NASA's Field Centers; about half of the positions had already moved or were in the process of moving. In October 1996, a major Agency-wide restructuring took place that aimed to reduce NASA Headquarters staffing and transfer most technology development and commercialization activities to individual program offices and Field Centers.[24] The Office of Space Communications (Code O) merged into the Office of Space Flight, becoming another division at the same level as the Space Station program, Space Shuttle program, and Advanced Projects office.[25] The new Communications Division was headed by David W. Harris, who had previously led the Program Integration Division in the Office of Space Communications.

At the same time, the Office of Space Access and Technology (Code X), where the RLVs program was located, was disbanded. Work into space research and technology returned to Code R, now renamed the Office of Aeronautics and Space Transportation Technology. A Space Transportation Technology organization was created as well as a Space Transportation Division, both headed by Payton, who had headed the Space Transportation division in Code X. The Advanced Space Transportation office, charged with NASA's X-33 and X-34 launch vehicle technology development programs, was relocated to Code R.

Trafton resigned as Associate Administrator of the Office of Space Flight in November 1997. Joseph H. Rothenberg, Director of Goddard Space Flight Center, was appointed to the position in January 1998, becoming NASA's fourth Associate Administrator for the Office of Space Flight in little more than three years. In July 1998, the Office of Space Flight reorganized into four functional offices: 1) Operations, headed by William Readdy, which included ELVs, led by Karen Poniatowski; Space Communications, headed by Robert Spearing; and Space Operations Utilization, led by Robert L. Elsbernd; 2) Enterprise Development, led by Darrel Branscome, which included Advanced Projects, Strategic Planning, and Outreach 3) Business Management, led by Michael Reilly; and 4) Development, led by Gretchen McClain; (see Figure 2–8).

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[24] Anne Eisele, "Restructuring Would Slash Headquarters," *Space News* (July 1–7, 1996): 4.

[25] Charles T. Force, Associate Administrator for the Office of Space Communications (Code O), had resigned from NASA in May 1996, before the announcement of the merger of Code O into Code M. "Force To Leave NASA," *NASA News* Release 96–88, May 3, 1996, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1996/96-88.txt* (accessed March 3, 2005).

Money for NASA's Launch Systems

Budget Structure

The federal appropriation categories funding NASA space transportation and launch programs and activities changed in the mid-1990s. For the first four years of the 1989–1998 decade, they were funded by R&D and SFC&DC appropriations. With the FY 1993 budget year, NASA changed its appropriation categories to HSF, which included all Space Shuttle activities, and SAT, which included experimental or development initiatives.[26] ELVs also fell within the SAT appropriation until 1998, when it moved to HSF.

When NASA began using HSF and SAT appropriations, the names and descriptions of many of the subordinate programs and budget categories remained as they had been with the R&D and SFC&DC budget structure. Exceptions are noted below each table. If it is unclear whether a new budget category was merely a name change or whether it indicated a new or modified program, the new name is treated as a new budget category.

A large portion of NASA's budget went to fund Space Shuttle activities, and most space transportation budget categories in the annual budget relate to the Space Shuttle. Expendable launch systems received relatively little attention because NASA obtained most expendable launch services from the commercial sector. The main focus of non-Shuttle launch services in the annual budget related to the mission is to develop new and alternative reusable launch systems and reduce the cost of access to space.

In most cases, the authorization and appropriations bills funding NASA's programs addressed only major budget categories and did not provide much detail regarding where funds should be spent. Authorization bills provided more detail than appropriations bills, at least showing amounts for Space Transportation Capability and Development in the R&D appropriation and for Space Shuttle Production and Operational Capability and Space Shuttle Operations in the SFC&DC category. When the appropriation categories changed to HSF and SAT, the authorization bills typically provided amounts for Payload and Utilization Operations; Space Shuttle Safety and Performance Upgrades; Shuttle Production and Operational Capability; and Space Shuttle Operations in the HSF appropriation. In the SAT appropriation, Congress provided amounts for Advanced Concepts and Technology (Space Access and Technology). Congress only occasionally indicated that a particular amount was authorized for a specific project. Amounts for ELVs and launch services were occasionally provided separately, but many were not budgeted separately from the larger categories.

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[26] These appropriations funded additional NASA programs.

Authorization bills provided more detail than appropriations bills, which provided almost no detail. Appropriations bills generally gave a total amount only for R&D and another for SFC&DC. After the change in appropriation categories, they gave an amount for HSF and one for SAT.

Congress based total authorized and appropriated funding on NASA's annual budget estimates provided to the President and presented to Congress. These detailed estimates formed the basis for NASA's operating plan and the amounts each program would actually spend. The House and Senate subcommittees and committees used these budget estimates for their discussions and often prepared reports dealing with the estimated amounts; but except where specific amounts were included in the authorization or appropriations bills, these reports did not legally require NASA to spend funds in a certain way except in very broad categories.

Phase I: FY 1989–FY 1992

During this period, the R&D and SFC&DC appropriations funded NASA's launch systems, as well as other NASA programs. The R&D appropriation funded Space Shuttle programs in the Space Transportation Capability Development category. These included activities such as the Tethered Satellite System; Spacelab; development and procurement of upper stages; engineering and technical base support at the human spaceflight NASA Centers (Johnson Space Center, Kennedy Space Center, Marshall Space Flight Center, and Stennis Space Center); payload operations and support equipment; studies into advanced launch systems; and other advanced programs and development activities. Space Transportation Capability Development also funded all Space Station activities (discussed in chapter 3).

The SFC&DC appropriation funded the operational activities of the Space Transportation System. The system's two major elements were Shuttle Production and Operational Capability and Space Transportation (Shuttle) Operations. Shuttle Production and Operational Capability provided for the fleet of orbiters; main engines; launch site and mission operations requirements; spares; production tooling; and related supporting activities. The appropriation also provided funds for development of an Advanced Solid Rocket Motor. Space Transportation Operations included standard operational support services for the Space Shuttle and the procurement of ELVs. This budget category funded the production of flight hardware, overhaul and repair of equipment, and labor and materials needed for flight and ground operations. The SFC&DC appropriation also was used to fund the tracking and communication systems used for all NASA flight projects.

Phase II: FY 1993–FY 1998

In FY 1993, R&D and SFC&DC budget items involving space transportation were placed into a new HSF appropriation or into the Science, Applications and Technology appropriation. The HSF appropriation included the on-orbit infrastructure (Space Station and Spacelab), transportation capability (Space Shuttle program, including operations, program support and performance, and safety upgrades), and the Russian Cooperation program (which included flight activities associated with the cooperative research flights to the Russian *Mir* Space Station). HSF appropriation activities were funded in the following major budget line items: 1) Space Station, 2) Russian Cooperation, 3) Space Shuttle, and 4) Payload Utilization and Operations. The Space Shuttle budget had two major categories: Safety and Performance Upgrades and Space Shuttle Operations. Safety and Performance Upgrades corresponded most closely with the old SFC&DC Shuttle Production and Operational Capability budget category. Payload Utilization included funding to support payloads flying on the Shuttle and Spacelab, as well as advanced technology projects and engineering technical base support for the Field Centers supporting HSF flight activities. Space Station, Russian Cooperation, and Spacelab are discussed in chapter 3. Space Shuttle and the Payload Utilization and Operations activities are discussed in this chapter.

The new SAT appropriation provided funding for NASA's research and development activities, in particular, "to extend knowledge of the Earth, its space environment, and the universe; and to invest in new technologies, particularly in aeronautics."[27] The two categories in the SAT appropriation most directly related to space transportation or launch systems were 1) Advanced Concepts and Technology (as it was called in FY 1995) or Space Access and Technology (beginning in FY 1996), and 2) Launch Services, consisting primarily of the ELV budget formerly included in the SFC&DC appropriation. Launch Services sometimes appeared in budget documents as a separate budget category under the SAT appropriation. At other times, it was shown as a subcategory in the Office of Space Science and Applications. Notes below the funding history tables that follow identify items funded from the SAT appropriation.

Funding History

For the 1989–1991 fiscal years, funding increased for launch systems and, in particular, the Space Shuttle. Payload operations and support declined slightly as did upper stages. Space Transportation Capability Development in the R&D appropriation peaked in 1991 at $763,400,000. In the SFC&DC appropriation, Space Shuttle Production and Operational Capability reached its high of $1,364,000,000 in 1991. Funding for Space Transportation Operations continued to rise for two more years, reaching its high of $3,085,200,000 in 1993. ELV funding, which had dropped in 1993, rose in 1994 to $300,300,000.

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[27] "General Statement," *National Aeronautics and Space Administration, Science, Aeronautics and Technology, Fiscal Year 1995 Estimates*, p. SAT SUM-1.

In 1992, the downward slide for Space Shuttle operations began as rising costs for the Space Station drained the budget. The SFC&DC Space Shuttle Production and Operational Capability authorization dropped from $1,364,000,000 in FY 1991 to $1,328,900,000 in FY 1992. The amount authorized for Space Transportation Capability Development dropped from $763,400,000 in the FY 1991 authorization to $679,800,000 in FY 1992; it rose somewhat in FY 1993 to $733,700,000 and almost to its FY 1991 level in FY 1994, reaching $7,509,300,000. The amount for Space Shuttle Operations continued to rise until FY 1994, when it dropped from $3,085,200,000 to $3,006,500,000.

In FY 1995, appropriated amounts used the new HSF appropriation categories, which covered the operational end of launch systems, and SAT for developmental areas of space transportation. It was clear that, beginning with FY 1995, the HSF budget dropped considerably. Between FY 1995 and FY 1997, the appropriated amount decreased from $5,592,900,000 to $5,362,000,000. This included a $94 million general reduction taken from Space Shuttle operations.[28] The decline reflected a concerted Clinton administration effort to reduce the deficit while dealing with greater costs for the Space Station. The FY 1996 appropriation, coming at the end of an arduous six months of discussions that included 14 continuing resolutions and two government shutdowns, allotted HSF 1 percent less than NASA's request and 1.1 percent less than its FY 1995 amount. This decrease took place even though the Space Station received 1.1 percent more than it had in FY 1995, making the cuts to the Space Shuttle program even more pronounced.[29] The amount appropriated to SAT, which handled work on new RLVs, rose in FY 1997, but dropped in FY 1998 from $711,000,000 to $696,000,000. At the same time, in FY 1998, the appropriation for HSF rose again to $5,506,500,000.

The following tables reflect the budget categories as broken down by NASA and authorized by Congress. Table 2–1 shows congressional action. Notes below the table indicate when amounts were appropriated rather than authorized. Table 2–2 shows programmed amounts. These amounts formed NASA's operating plan, i.e., what NASA budgeted for particular activities during a fiscal year. On both these tables, the reader should not assume that subordinate amounts below a major budget category equal the amount shown above in the major budget category. Some subordinate budget categories are not launch-related and are not included in these tables.

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[28] "Senate Appropriators Approve $14.4 Billion for NASA," *Aerospace Daily* (July 15, 1994): 79.

[29] "Results of FY 1996 Appropriations Process," *The American Institute of Physics Bulletin of Science, Policy News,* no. 86 (May 30, 1996), *http://www.sdsc.edu/SDSCwire/v2.12/FY96results.html* (accessed March 14, 2005).

The following series of tables show the amounts NASA submitted in its annual budget estimates (see Tables 2–3 through 2–57). NASA submits a budget estimate two years before the start of each fiscal year and then a revised estimate a year later. The tables show both the original and revised estimates, separated by a forward slash. If only one amount is shown (either before or after the forward slash), NASA's budget estimate documents referenced that budget category only once—either in its original budget estimate, shown before the forward slash. or in the revised budget estimate, shown after the forward slash. If a category was mentioned in an authorization bill, that amount is shown.

Authorized and appropriated amounts come from the appropriate authorization or appropriations bill.[30] If no authorized or appropriated amount is shown for a particular category, then the bills did not address that category. Submitted and programmed amounts come from the annual NASA budget estimates. NASA appropriations were included with the Department of Veterans Affairs, Housing and Urban Development, and Independent Agencies appropriations bills for the fiscal year. If no programmed amount is shown, that year's budget did not include a programmed amount for the particular budget category. See the individual budget tables for details.

Expendable Launch Vehicles

Overview

By NASA's fourth decade, America's ELVs were obtained either from the DOD stockpile of retired rockets and modified for space launch purposes or were procured from the private sector according to criteria in NASA's FY 1991 Authorization Act and Launch Services Purchase Act (LSPA) of 1990.[31] The LSPA required NASA to purchase launch services for its primary payloads from commercial providers. This legislation quickly opened up a new market to American industry as the government no longer competed as a launch services provider. Within six months after its passage, one launch services provider, General Dynamics, had decided to fund the construction of 60 new Atlas launch vehicles although it did not yet have a single buyer for the vehicles. Other launch vehicle providers followed suit. In November 1990, NASA signed a contract with McDonnell-Douglas to provide at least three Delta IIs. In September 1991, a contract with Orbital Sciences Corporation was signed for seven Pegasus vehicles. NASA contracted with Martin Marietta in 1994 for intermediate-class launch services on Atlas vehicles, and Orbital Sciences was selected to provide ultra-lite ELV launch services the same year.

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[30] Authorization and appropriations bills are available at *http://thomas.loc.gov.*

[31] The Launch Services Purchase Act of 1990 was Title II of the FY 1991 Authorization Act. *National Aeronautics and Space Administration Authorization Act, Fiscal Year 1991*, 101st Congress, 2nd sess., Public Law 101-611 (November 16, 1990).

In the first years following NASA's 1988 return to flight, NASA acquired ELVs noncompetitively for the scientific missions remanifested onto ELVs from the Space Shuttle. NASA acquired all subsequent ELV launch services competitively from the private sector in the small, medium, and intermediate-performance classes, which could launch payloads up to 30,000 pounds (13,600 kilograms). Larger payloads up to 39,000 pounds (17,690 kilograms) were launched aboard the Titan IV/Centaur launch vehicle, developed by Martin Marietta Corporation (later Lockheed Martin). These were acquired from the U.S. Air Force by means of a contract the Air Force had with Martin Marietta since large class launch services were not available directly from the private sector.[32]

During NASA's fourth decade, 215 launches on American ELVs and one joint U.S.-French ELV launch on a European Ariane rocket took place. Almost 94 percent of these launches succeeded. Eight families of ELVs: Athena; Atlas; Conestoga; Delta; Pegasus; Scout; Taurus; and Titan were used. They each had impressive success rates with very few failures. The large majority carried either DOD or commercial payloads. Launch vehicle performance is shown in Figure 2–9 and Table 2–58. ELV activities are summarized in the following section. Some references use the term "partial failure" to discuss specific launches. To allow inclusion in this table and in the graph that follows, each launch is classified as either a success or failure. Partial failures are explained in footnotes below the table.

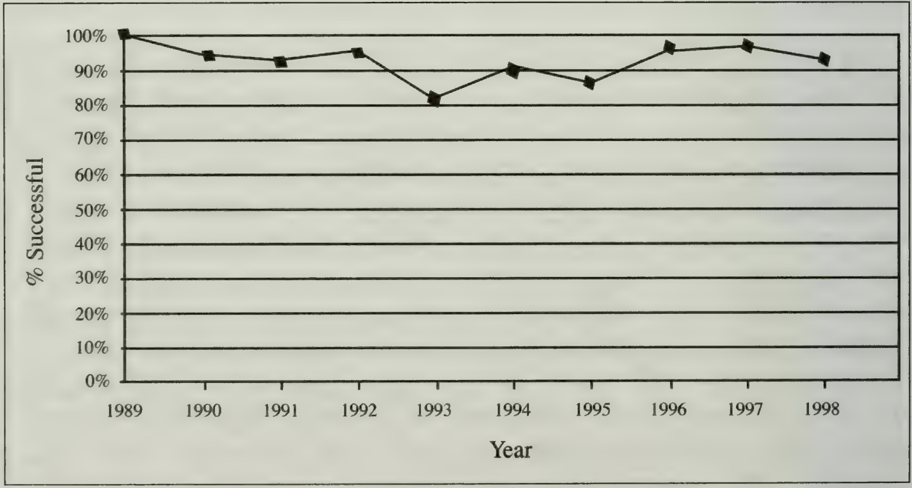

Figure 2–9. Expendable Launch Vehicle Success Rate.

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[32] "Space Transportation Operations," *National Aeronautics and Space Administration Fiscal Year 1991 Budget Estimates*, pp. SF 2–11.

1989

In 1989, there were 13 U.S. ELV launches on known launch vehicles: 8 Deltas, 4 Titans, and 1 Atlas. All were successful. One was a NASA scientific spacecraft and one a commercial launch. The remaining launches were DOD satellites.

1990

In 1990, there were 21 U.S. ELV launches: 11 Deltas, 5 Titans, 3 Atlases, 1 Scout, and 1 Pegasus. One Titan launch failed. The launches included one joint NASA–Germany space science satellite, and two joint NASA–DOD environmental research satellites. The remaining satellites were either DOD satellites or commercial communications satellites.

1991

Twelve satellites launched on ELVs in 1991: 5 Deltas, 2 Titans, 4 Atlases, 1 Scout, and 1 Pegasus. One was a NASA launch of a meteorological satellite. The remaining satellites were either DOD or commercial spacecraft. One Atlas launch failed.

1992

Twenty-one satellites launched on American ELVs in 1992: 11 Deltas, 3 Titans, 5 Atlases, and 2 Scouts. Four payloads were science missions. The others were DOD or commercial payloads. One Atlas launch failed. In addition, a joint U.S.–French scientific spacecraft launched on a European Ariane ELV from the Kourou launch complex in French Guiana.

1993

Eighteen satellites launched on American ELVs in 1993: 7 on Deltas, 6 Atlases, 2 Titans, 2 Pegasus, and 1 Scout. One launch was a Department of Energy science payload, two were NASA earth science payloads, and the rest were DOD or commercial payloads. Both Titan launches failed.

1994

In 1994, 20 spacecraft launched on American ELVs: 3 Deltas, 5 Titans, 7 Atlases, 1 Taurus, 1 Scout, and 3 Pegasus. One was a NASA meteorological satellite, one a space science satellite, and the remainder either DOD or commercial satellites. There was one Pegasus launch failure and one Pegasus that inserted its payload into a lower-than-specified orbit.

1995

In 1995, 23 spacecraft were launched on American ELVs—3 were Deltas, 4 Titans, 12 Atlases, 2 Pegasus, 1 Athena, and 1 Conestoga. Payloads included one NASA meteorological satellite, one Canadian remote sensing satellite, two NASA science satellites, and the remainder DOD or commercial satellites. The Athena I, Conestoga, and one of the Pegasus XL launches failed.

1996

There were 26 ELV launches in 1996: 10 Deltas, 7 Atlases, 4 Titans, and 5 Pegasus launches. There were eight science payloads including one joint Italian–Dutch telescope. The rest were DOD or commercial satellites. One Pegasus XL launch failed.

1997

In 1997, 30 spacecraft were launched on ELVs: 11 Deltas, 8 Atlases, 5 Titans, 5 Pegasus, and 1 Athena. These included three Earth science payloads and two space science missions. The remainders were DOD or commercial satellites. One Delta launch failed.

1998

There were 31 ELV launches in 1998: 13 Deltas, 6 Atlases, 3 Titans, 1 Athena, 2 Taurus, and 6 Pegasus. These included five space science payloads and one meteorological payload. The rest were DOD or commercial satellites. One Titan and one Delta, the first Delta III, failed.

Expendable Launch Vehicle Characteristics

The following sections describe each family of U.S. ELVs used from 1989 through 1998. It should be noted that the figures cited in the Launch Characteristics tables are approximations and may not be accurate for all vehicles within a particular model of launch vehicle. Many factors influence detailed specifications. Each payload is different, and the payload size as well as its ultimate orbit will determine the launch vehicle configuration, including the number of stages and strap-on motors, the size of the selected fairing, and the nature of the attach fittings. Variations in payloads also determine the amount of propellant, the burn rate, thrust levels, and other parameters. Source material, although dependable, does not always state under what conditions a particular value is true. For instance, a value for thrust can indicate nominal, maximum, or average force and can exist during liftoff at sea level or in a vacuum. Different payloads and different orbits can also determine performance parameters. The maximum payload for a launch vehicle to low-Earth orbit may be different for a launch from Cape Canaveral, Florida, than for a launch from Vandenberg Air Force Base, California. There are also variations in what is considered low-Earth orbit. The *Aeronautics and Space Report of the President* and the Federal Communications Commission use a 185-kilometer (100-nautical-mile) orbit; other sources range from 144 kilometers to 196 kilometers (78 nautical miles to 106 nautical miles) or consider low-Earth orbit to be the orbit flown by the Space Shuttle.[33]

Measurements are stated in the original units used in the source material. Some measurements will appear as English units and some as metric units. The conversion to the other unit of measure follows in parentheses.

This chapter uses the following abbreviations for propellants: LH_2 = liquid hydrogen, LOX = liquid oxygen, N_2H_2 - = hydrazine, N_2O_4 = nitrogen tetroxide, RJ-1 = liquid hydrocarbon, and RP-1 = kerosene.

Athena Launch Vehicle

The Athena launch vehicle was a privately funded solid-propellant launch vehicle developed by Lockheed Martin beginning in 1993 to carry small to medium payloads into low-Earth, geostationary transfer, and interplanetary orbits. It was initially called the Lockheed Launch Vehicle (LLV) and then the Lockheed Martin Launch Vehicle (LMLV) after Lockheed merged with Martin Marietta in 1994. The core launch vehicle was called LMLV-1, later renamed Athena I. A larger version, the LMLV-2, was renamed Athena II.

Both vehicle models used a 92-inch (234-centimeter)-diameter fairing, and both used solid motors and a small liquid injection stage called the orbit adjust module as its top stage. The top stage contained the altitude control and avionics subsystems. The Athena I and Athena II both had a Castor 120 first stage, a commercial motor made by Thiokol derived from the Peacekeeper intercontinental ballistic missile first-stage motor and modified for space launch use. The Athena II's second stage was another Castor 120. The second and third stages of the Athena I were the same as the third and fourth stages of the Athena II: a Pratt & Whitney Orbus 21D motor and an orbit adjust module powered by four Primex MR-107 engines using hydrazine fuel. The orbit assist module was available with four or six propellant tanks, depending on mission requirements. Figure 2–10 shows the Athena I and Athena II configurations.

The first Athena I launch took place on August 15, 1995. This launch failed when the thrust vector control system failed. The first successful launch was on August 23, 1997, from Vandenberg Air Force Base. Its payload, the Lewis satellite, failed shortly after launch. Later launches of Athena I were planned to take place from the Kodiak Launch Complex in Alaska.

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[33] "Glossary," NASA Life Sciences Data Archive, *http://lsda.jsc.nasa.gov/kids/L&W/glossary.htm* (accessed February 9, 2005). Also "Genesis: Search for Origins," Jet Propulsion Laboratory, *http://www.genesismission.org/glossary.html* (accessed February 9, 2005).

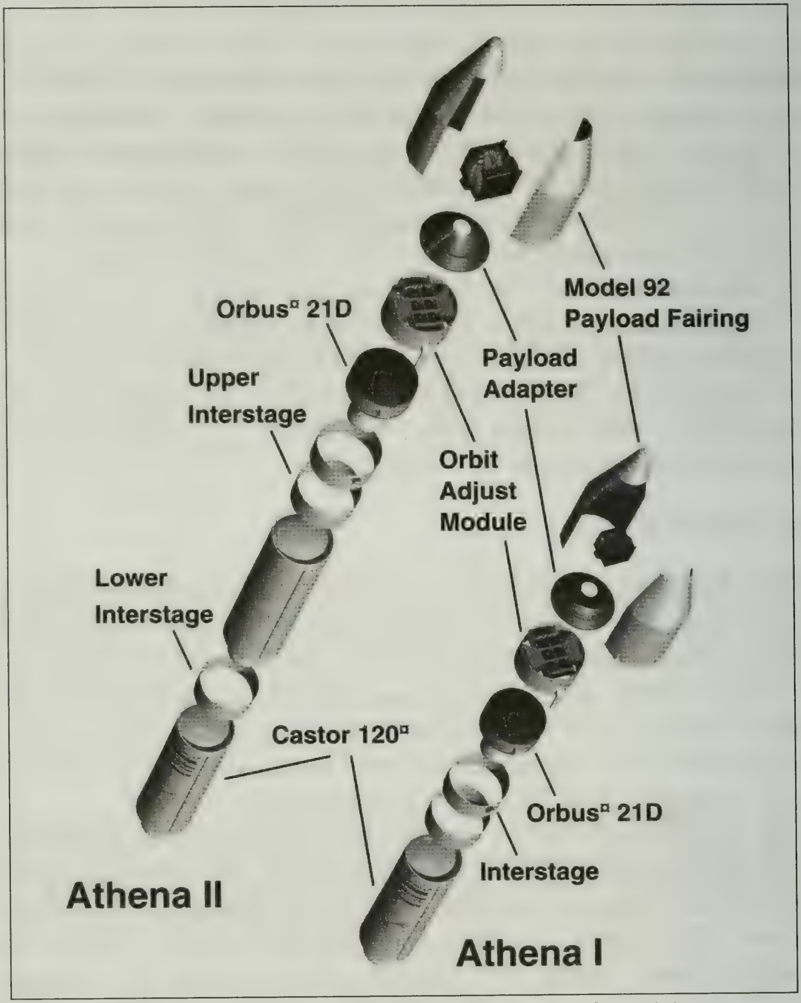
Model 92
Payload Fairing
Orbus® 21D
Payload
Adapter
Upper
Interstage
Orbit
Adjust
Module
Lower
Interstage
Castor 120®
Orbus® 21D
Interstage
Athena II
Athena I

Figure 2–10. Athena I and Athena II. (Lockheed Martin)

Athena II successfully launched NASA's Lunar Prospector into orbit from Cape Canaveral Air Station on January 7, 1998. The Athena II's third stage enabled it to launch larger payloads. Table 2–59 lists Athena launches. Tables 2–60 and 2–61 list Athena I and Athena II characteristics.

The Atlas Family

The Atlas rocket was America's first intercontinental ballistic missile (ICBM). The Air Force used the missile only briefly as an ICBM, however, and made its surplus rockets available for use as space launch vehicles in the 1980s after adding an upper stage allowing the modified rockets to place various types of payloads into low-Earth orbit.

The surplus rockets were used quickly in their new role, and only a few Atlas E and Atlas G Centaur launch vehicles remained in the surplus inventory by the end of the 1980s. NASA used these remaining rockets and then started using new Atlas I, II, IIA, and IIAS launchers.

The production of Atlas rockets was government-initiated through the production of the Atlas G Centaur. The commercial sector took over launch services in June 1987. The first commercial launch took place in July 1990 with the first Atlas I rocket.[34]

The Convair Division of General Dynamics built Atlas rockets at the beginning of the program. Martin Marietta acquired Convair's launch vehicle division in 1994 and took over Atlas production until Martin Marietta merged with Lockheed in 1996 to form Lockheed Martin, the current Atlas producer. All Atlas models, except the Atlas E, used the liquid-fueled Centaur as their upper stage to provide added thrust. This upper stage, developed by General Dynamics for NASA, had been used since the 1960s. The Atlas E used solid-fueled apogee kick motors to supply extra power.

The Atlas I was the first Atlas product using a new naming convention, initiated when Lockheed began using the Atlas for commercial launches in the late 1980s. Rather than use the old letter designation for its rockets (Atlas E, F, and G, for example), Lockheed began using Roman numerals. A letter after the Roman numeral designated different variations in each family, such as Atlas IIA and Atlas IIAS, in which "S" indicated a strap-on motor.

The Atlas has been a dependable launch vehicle with only a few launch failures. Table 2–62 lists all Atlas launches between 1989 and 1998.

Atlas Characteristics

The Atlas launch vehicle system consisted of the Atlas booster (composed of a booster and a sustainer section), the Centaur upper stage, the payload fairing, and an interstage adapter located between the booster/sustainer stage and the Centaur stage. The launch vehicle was typically called a "one-and-a-half"-stage vehicle. The booster stage engines flanked the smaller sustainer engine and did not carry any propellant. The sustainer section contained propellant tanks for both the booster and sustainer burns. All engines ignited at liftoff, and the two smaller vernier engines on the Atlas E and G and Atlas I models ignited seconds later.[35] This differed from later rockets in which the stages fired sequentially.

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[34] "Atlas," Lockheed Martin Space Systems Company, *http://www.lockheedmartin.com/wms/findpage.do?dsp=fec&ci=14917&5c=400* (accessed July 18, 2006).

[35] The "I" in Atlas I refers to the Roman numeral "one," not the letter "I."

Atlas E

Atlas E was first used as a launcher in 1960. The last Atlas E launch took place on March 24, 1995, when it launched a military weather satellite into orbit. All Atlas E launches during this period took place from Vandenberg Air Force Base in California. The Atlas E was the only Atlas launch vehicle during this period not using a Centaur upper stage. It obtained additional boosting power from its apogee kick motor (AKM). Dimensions stated in Table 2–63 are approximate because more than one AKM model was used and fairings varied in length.

Atlas G Centaur

The Atlas G Centaur, used primarily to launch communications satellites, was an improved version of the earlier Atlas Centaur launch vehicle. It was 81 inches (2.06 meters) longer than its predecessor to allow greater fuel capacity and had increased booster thrust of 7,500 pounds (33.36 kilonewtons), leading to a total liftoff thrust of 438,877 pounds (1,950 kilonewtons).[36]

The Atlas G Centaur was first used in 1984 with an Intelsat satellite. The final Atlas G Centaur launch took place on September 25, 1989, with the launch of Fltsatcom-8. This launch marked the last NASA-managed ELV launch. From then on, NASA purchased launch services from a series of contractors. Table 2–64 shows Atlas G Centaur characteristics.

Atlas I

The Atlas I was the first of a new family of launch vehicles that could boost payloads into low-Earth orbit, geosynchronous-Earth orbit, and on interplanetary trajectories. The launch vehicle was very similar to the Atlas G Centaur, and it included two boosters, a sustainer, two vernier single-start engines, and a Centaur upper stage. An interstage adapter separated the Atlas stage from the Centaur. The vehicle had two new payload fairings, incorporated significant improvements in the guidance and control systems, and replaced analog flight control components with digital units interconnected with a digital data bus. Figure 2–11 shows an Atlas I. Table 2–65 lists Atlas I characteristics.

The first Atlas I flight took place on July 25, 1990, with the launch of the Combined Release and Radiation Effects Satellite (CRRES), a joint NASA-U.S. Air Force project. The final Atlas I launch took place on April 25, 1997, with the launch of GOES-10 into geosynchronous orbit. Although launch parameters varied slightly depending on launch date, launch time, and payload weight, Table 2–66 presents a typical launch sequence for a geosynchronous mission.

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[36] "Atlas," GlobalSecurity.org, *http://www.globalsecurity.org/space/systems/atlas.htm (accessed* January 26, 2005).

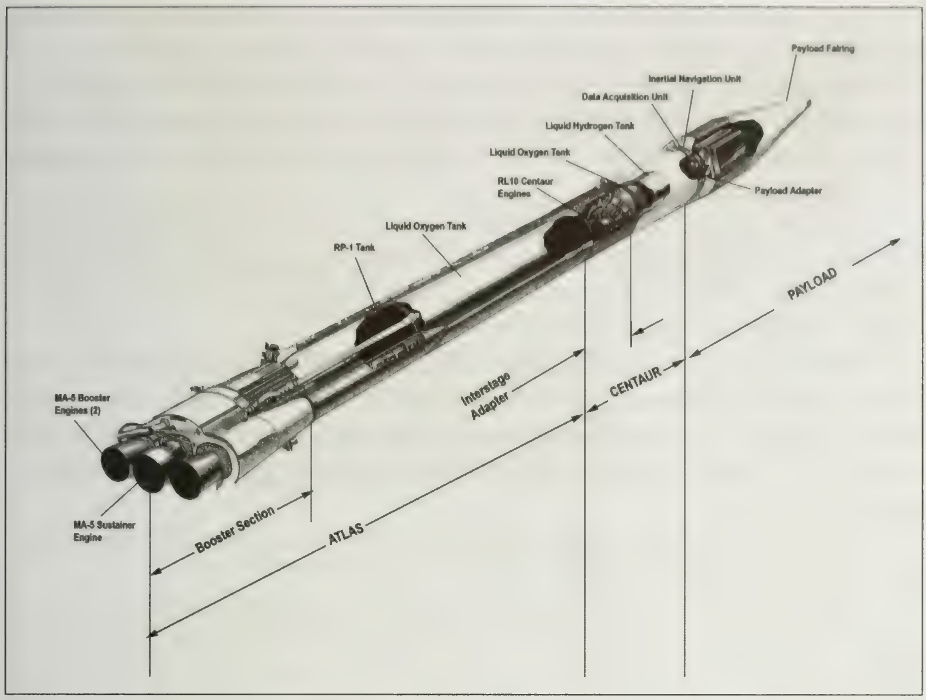
Payload Fairing
Inertial Navigation Unit
Data Acquisition Unit
Liquid Hydrogen Tank
Liquid Oxygen Tank
RL10 Centaur Engines
Payload Adapter
Liquid Oxygen Tank
RP-1 Tank
MA-5 Booster Engines (2)
MA-5 Sustainer Engine
Booster Section
ATLAS
Interstage Adapter
CENTAUR
PAYLOAD

Figure 2–11. Atlas I Components.

General Dynamics produced eleven Atlas I ELVs before the program shifted to Atlas II production. Three Atlas I launches failed to propel their payloads into orbit.

Atlas II Series

The Atlas II series consisted of the Atlas II, the Atlas IIA, and the Atlas IIAS models. Development of the first of these vehicles began in June 1988. They were originally developed to launch the Air Force Defense Satellite Communications System satellites, part of the Air Force Medium Launch Vehicle II program.

The Atlas II launch vehicles were an improved version of the Atlas-Centaur rockets. They provided higher performance by using engines with greater thrust and longer fuel tanks for both the Atlas and Centaur stages. This resulted in increased payload capability. The Atlas II replaced the MA-5 propulsion system used in the Atlas I with the improved MA-5A system. The Atlas II also replaced the vernier engines of Atlas I and earlier Atlas vehicles with a hydrazine roll control system located on the Atlas II interstage that had lower-cost electronics and an improved flight computer.

The Atlas II had a longer booster than the Atlas I for greater fuel stage-one capacity and used upgraded MA-5A engines, improved structures, and a new stabilization system. It also featured a lengthened Centaur upper stage that held more fuel and thus had better upper-stage performance.[37] The Atlas II was the only Atlas to use two R-4D attitude control thrusters for attitude and orbit adjustments.

The first Atlas II flew December 7, 1991, launching Eutelsat II F3. The last Atlas II launch took place March 16, 1998, with the launch of USA 138 (UHF-8), a communications satellite for DOD that replaced the old FLTSATCOM satellites.

With Atlas II, the manufacturers changed the terminology referring to the number of stages although the configuration remained essentially the same as earlier vehicles. The vehicle was then referred to as having "two-and-a-half" stages. These stages consisted of the booster, sustainer, interstage, and Centaur upper stage.

A total of 10 Atlas II launches took place; all were successful. Table 2–67 lists Atlas II characteristics.

The Atlas IIA was the commercial version of the Atlas II. It incorporated higher performance RL10 engines and optional extendible nozzles that provided added thrust to the Centaur upper stage. The first Atlas IIA flight took place on June 8, 1992, with the launch of Intelsat-K. Through the end of 1998, 15 Atlas IIA launches took place; all were successful. Table 2–68 lists Atlas IIA characteristics.

The Atlas IIAS was similar to the earlier Atlas IIA launch vehicle except that this model used four additional strap-on Castor IVA solid rocket boosters (SRB), which provided an average thrust of 433.7 kilonewtons (97,500 pounds) each. These SRBs fired two at a time. The first pair fired at liftoff. The second pair fired during flight after the first pair had burned out, approximately 54 seconds after liftoff. Both pairs were jettisoned soon after each pair burned out. The structure of the first stage was stronger to accommodate the SRBs. Table 2–69 lists Atlas IIAS characteristics. Figure 2–12 shows the Atlas IIAS configuration for the launch of the Solar and Heliospheric Observatory (SOHO) on December 2, 1995.

The first Atlas IIAS launched Telstar 401 on December 15, 1993. Through the end of 1998, 14 Atlas IIAS launches had taken place; all were successful.

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[37] "The Evolution of Commercial Launch Vehicles," *Fourth Quarter 2001 Quarterly Launch Report, http://ast.faa.gov/files/pdf/q42001.pdf* (accessed January 17, 2005).

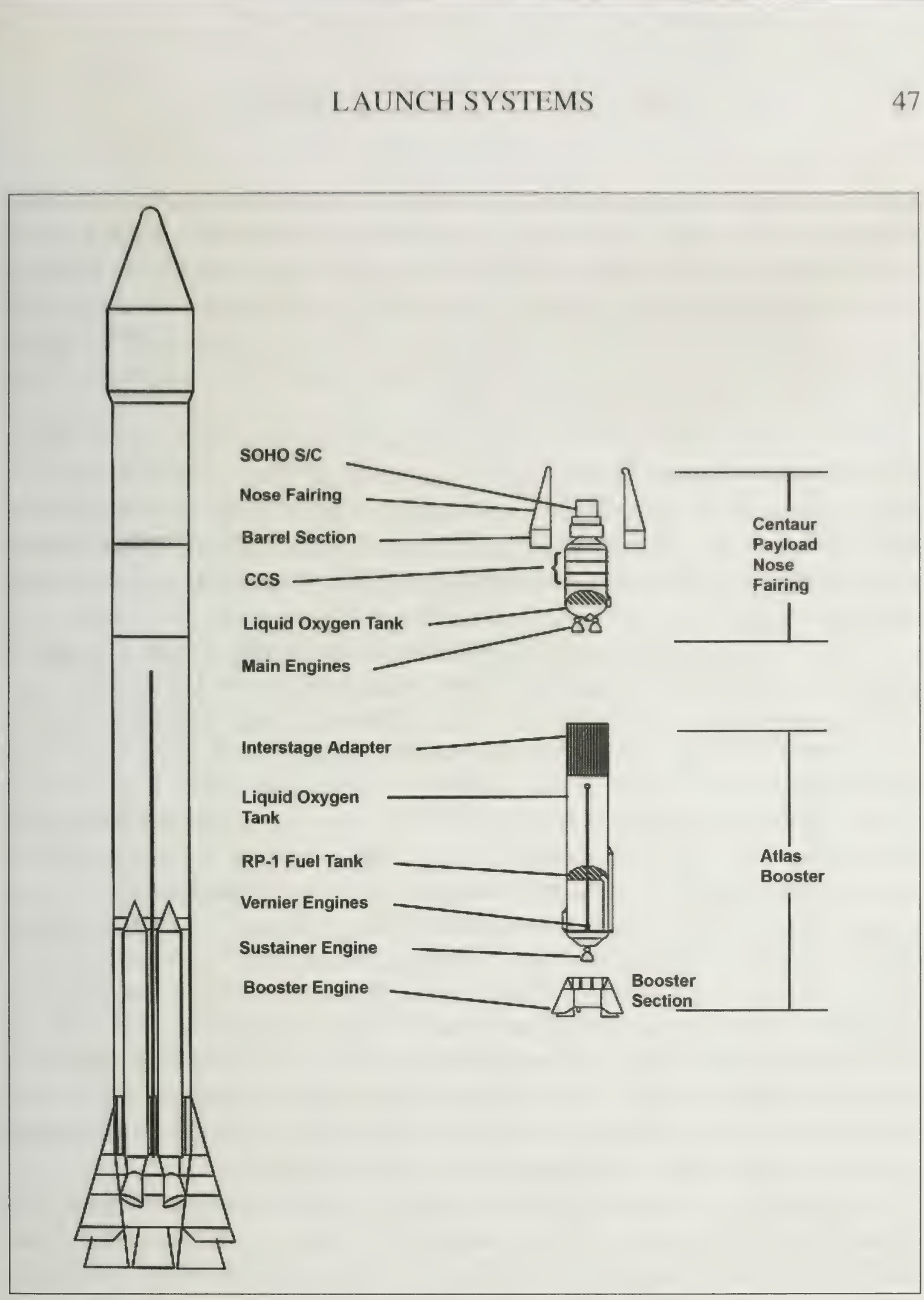
SOHO S/C
Nose Fairing
Barrel Section
CCS
Liquid Oxygen Tank
Main Engines
Centaur Payload Nose Fairing
Interstage Adapter
Liquid Oxygen Tank
RP-1 Fuel Tank
Vernier Engines
Sustainer Engine
Booster Engine
Booster Section
Atlas Booster

Figure 2–12. Atlas IIAS Launch Vehicle–SOHO Configuration, December 2, 1995. (NASA)

Conestoga Launch Vehicle

The Conestoga was a solid-propellant commercial launch vehicle that attempted to launch the Multiple Experiment Transporter to Earth Orbit and Return (METEOR 1) payload originally known as COMET for Commercial Experiment Transporter into low-Earth orbit in 1995. The privately funded launcher was designed to answer a need by the civilian and military community for a vehicle to launch small size orbital and suborbital payloads (500 pounds to 5,000 pounds) into low-Earth orbit. In 1982, Space Systems Inc. (SSI), managed by Mercury astronaut Donald "Deke" Slayton, successfully launched a single-stage, solid-fueled rocket as a test, ejecting its payload as planned.[38] The rocket was based on an Aerojet M56-A1, the second stage of a Minuteman ICBM. The company was the first to obtain a commercial launch license, in 1985 receiving Department of Transportation mission approval. In 1986, SSI signed the industry's first agreement to use a U.S. Government launch range, Wallops Flight Facility on the Eastern Shore of Virginia, as a commercial launch site.[39]

In November 1990, EER Systems purchased SSI, integrating it into EER's Space Systems Group. In 1991, NASA selected EER to provide Conestoga launch services for its METEOR satellite, a microgravity carrier program. METEOR was to be a recoverable payload, designed for on-orbit microgravity experiments that advanced commercial applications of materials processing and medical research.[40]

The Conestoga launch vehicle had a modular design, which provided a wide range of configurations for various purposes. It's Thiokol booster stage rockets consisted of one core Castor IVB surrounded by a combination of two to six more strap-on Castor IVA or IVB solid rocket motors. A Star 37, 48, or 63 upper stage motor sat immediately above the core booster motor. Four strap-on motors ignited at launch; they were followed by two more, and finally the central Castor. A cold gas reaction control system, located within the payload attach fitting, controlled pitch, yaw, and roll during fourth stage coast, burn, and payload separation. The hydrazine maneuvering and attitude control system sat above the Star motor upper stage and provided velocity augmentation and control of pitch, yaw, and roll. The avionics power, electronics, and guidance equipment were within the payload attach fitting. An aerodynamic payload fairing available in several sizes covered all components from the payload down to and including the Star motor. Varying the number of strap-on motors and selecting the appropriate upper stage extended the Conestoga's performance range from 500 pounds to 5,000 pounds to low-Earth orbit.[41]

METEOR was originally planned as a three-mission project with the first launch initially scheduled for September 1992. However, late delivery of the solid rocket motors delayed completion of the launch vehicle. Management difficulties with the Center for Space Transportation and Applied Research (CSTAR) at the University of Tennessee (the commercial center that had proposed the mission and which provided oversight), as well as rising costs forced NASA to reduce the project to a single mission. Agency review of the project continued into 1994 as NASA Administrator Goldin announced that NASA would refuse to continue funding the project. There also was the question of liability if the reentry module landed outside the sparsely populated Great Salt Lake desert in Utah. Congress, however, released the needed funds on condition that the contractors agreed to waive NASA's legal liability. NASA also insisted that CSTAR depart from the program. After further discussion with the three contractors providing elements of the vehicle, NASA signed a sole source, fixed-price contract with EER Systems.[42]

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[38] Deke Slayton was one of the original Mercury astronauts but was relieved of his assignment and did not fly because of a heart condition. After he was cleared to resume full flight status in 1972, he made his first spaceflight as Apollo docking module pilot of the Apollo-Soyuz Test Project mission, July 15–24, 1975.

[39] Isakowitz and Samella, *International Reference Guide to Space Launch Systems,* 2nd ed., p. 220.

[40] U.S. Department of Transportation, Federal Aviation Administration, "Special Report: U.S. Small Launch Vehicles," *Commercial Space Transportation Quarterly Launch Report, 1st Quarter 1996, http://ast.faa.gov/files/pdf/sr_96_1q.pdf* (accessed November 2, 2005).

[41] M. Daniels and B. Saaverdra, "The Conestoga Launch Vehicle—A Modular Approach to Meeting User Requirements," AIAA-94-0893, 15th American Institute of Aeronautics and Astronauts International Communications Satellite Systems Conference, February 27–March 3, 1994.

After further delays, launch finally took place on October 23, 1995. It was the first orbital flight from Wallops Flight Facility in 10 years.[43] After a promising liftoff, the rocket went off course when its first stage steering mechanism ran out of hydraulic fluid and became inoperable. Forty-six seconds after liftoff, 23 kilometers off Virginia's coast at an altitude of 10 kilometers, the Conestoga broke apart. The destruction resulted in the loss of the METEOR and the 14 microgravity experiments on board. EER Systems left the launch business and abandoned the project. See Table 2–70 for characteristics of the Conestoga 1620, the model that carried the METEOR.

The Delta Family

NASA has used the Delta launch vehicle since 1960 and has regularly upgraded the vehicle as the need for payload capacity grew. The vehicle has a high success rate. In the decade from 1989–1998, 82 Delta launches took place with only two failures. Table 2–71 lists all Delta launches.

The 2900 series was planned as the last Delta series. However, because the Space Shuttle was not yet ready to become an operational space launcher and NASA needed a vehicle with heavier payload capacity, the Delta 3000 series was developed in the late 1970s and early 1980s for payloads that were too heavy for Delta 2000s but did not require the Atlas-Centaur. Because the 3000 series was considered an interim vehicle for medium-weight payloads, NASA not did finance its development and production but instead bought completed vehicles for its civilian and commercial launches from McDonnell Douglas, which obtained private financing for the series. Table 2–72 lists Delta 3920 characteristics.

Delta production formally ended at the end of 1984 when its production line at Huntington Beach, California, closed. But when the *Challenger* explosion brought out the need for launch alternatives, NASA decided to resume using ELVs and reactivated the Delta production line. At the same time, President Ronald Reagan announced that the Space Shuttle would stop carrying commercial payloads.

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[42] Andrew Butrica, "The Commercial Launch Industry, Technological Change, and Government-Industry Relations," *http://www.hq.nasa.gov/office/pao/History/x-33/butr02.htm* (accessed November 3, 2005).

[43] "Conestoga," GlobalSecurity.org, *http://www.globalsecurity.org/space/systems/conestoga.htm* (accessed November 3, 2005).

The commercial Delta era began in January 1987 when the U.S. Air Force announced its selection of McDonnell Douglas to produce seven Deltas IIs to launch its NAVSTAR Global Positioning System (GPS) satellites, originally manifested for the Space Shuttle. The initial contract expanded to 20 vehicles in 1988 when the Air Force exercised two contract options. In the interim, the remaining stock of older Deltas was modified for three missions: the Delta 4925 combined the earlier MB-3 engine with enhanced Castor IVA strap-on motors to launch the BSB-R1 and Insat 1-D satellites, and the Delta 5925 used Castors with the RS-27 engine to launch the Cosmic Background Explorer for NASA. On July 1, 1988, the Air Force officially received custody of Launch Complex 17, located at Cape Canaveral Air Force Station, Florida, from NASA and took over East Coast launch operations, ending 28 years of Delta launches managed by NASA.[44]

McDonnell Douglas built on its successful Delta 3920/PAM-D model to produce the Delta II. The first Delta II, the 6925, flew on February 14, 1989, launching the first of nine Air Force GPS satellites into orbit 20,200 kilometers (10,900 nautical miles) above Earth. NASA first contracted commercially for the Delta II in December 1990 for launch of its Geotail, Wind, and Polar science satellites, which launched in 1992, 1994, and 1996, respectively. NASA was the first U.S. government agency to procure commercial launch services.[45]

The first stage of the Delta 6925 was an 85.6-foot (26-meter)-long Extra Extended Long Tank powered by an RS-27 engine and augmented by nine Castor IVA strap-on motors. The second stage used an Aerojet AJ10-118K engine that delivered approximately 9,645 pounds (42.4 kilonewtons) of thrust. The third stage payload assist module (PAM)-D, equipped with a Thiokol Star 48B solid rocket motor, delivered approximately 15,100 pounds (67 kilonewtons) of thrust and made the vehicle suitable for geosynchronous and Earth-escape missions. Table 2–73 lists Delta II 6925 characteristics.

The versatile Delta II could be configured as a two-stage or three-stage vehicle and could launch with three or four strap-on motors as well as with the more common nine strap-ons. Both two-stage and three-stage Deltas could support 9.5-foot (2.9-meter) and 10-foot (3.05 meter)-diameter fairings. When nine strap-ons were used, six were ignited at launch and the remaining three ignited in flight. The 9.5-foot fairing was primarily designed for the three-stage Delta.[46] The 10-foot (3.05-meter) fairing was lighter than the one it replaced and was also available in a longer version for taller payloads. Typically, two-stage Deltas launched satellites to low-Earth orbit, while three-stage Delta IIs delivered payloads to geosynchronous transfer orbit or were used for deep-space missions.

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[44] "Delta Launch Complex Transferred to Air Force," *NASA News* Release 88-99, July 15, 1988. (NASA History Office Folder 010241).

[45] "Review notes from Charles Gunn September 1, 2005.

[46] "Boeing Delta II Medium Launch Vehicle," Delta II Backgrounder, *http://www.boeing.com/defensespace/space/delta/delta2/contour/mission_info/backgrounders/delta_2_backgrounder.htm* (accessed January 31, 2005).

Also, the Delta II could launch one or more payloads on the same launch vehicle by using a variety of payload attachments. Figure 2–13 shows the Delta II with nine strap-ons.

Several other Delta IIs were developed that eventually replaced the 6925: the 7326, 7420, 7425, the 7920, and the most powerful, the 7925. All Deltas in the 7000 series were equipped with an improved engine designated the RS-27A that boosted engine performance. Also, more power and longer Hercules (later Alliant Techsystems) graphite epoxy motors (GEMs) replaced the Thiokol Castor IVA solid rocket motors. Each GEM was 42.5 feet (13 meters) long and provided 446 kilonewtons (100,300 pounds) of thrust at liftoff (see Table 2–74 and Figure 2–14).[47] The 7925 first flew in November 1990 to launch a NAVSTAR GPS satellite. Other Delta missions launched satellites to Mars, toward asteroids and comets, and were used for Earth-observation and astronomy missions. Figure 2–15 compares the Delta 3920, Delta II 6925, and Delta II 7925.

In 1995, McDonnell Douglas began Delta III development to fulfill growing customer needs for a higher capacity commercial launch service.[48] With a payload delivery capacity to geosynchronous transfer orbit of 3,810 kilograms (8,400 pounds), the Delta III effectively doubled the performance of the Delta II. The first Delta III launch took place in 1998, but a successful launch did not occur until August 2000. Table 2–75 lists the sequence of events for a typical Delta launch to geosynchronous orbit.

Pegasus Booster

The Pegasus was the first all-new U.S. space launch vehicle since the 1970s and the only air-launched space booster vehicle attempted in the United States in approximately 30 years when the U.S. Navy attempted the unsuccessful Project Pilot. Considered the operational successor to the long-lived Scout launch vehicle in the small-payload, solid-propellant-motor category, the Pegasus was developed jointly by Orbital Sciences Corporation and Hercules Aerospace Company (later Alliant Techsystems of ATK Thiokol Propulsion Company).[49] Hercules was responsible for the design and production of the new solid rocket motors and the payload fairings. Orbital was responsible for the remaining mechanical and avionics systems, ground and flight software, the carrier aircraft interface, mission and vehicle integration, overall systems engineering, and program management. The development cost of more than $50 million was split evenly between the two partners.[50]

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[47] Mark Cleary, "Delta II Overview," in *Delta Space Operations at the Cape, 1993–2001, https://www.patrick.af.mil/heritage/DELTA%20II%20Overview.htm*, (accessed January 31, 2005).

[48] Boeing acquired the launch organization from McDonnell Douglas in 1997 and transferred production of the Delta to its facilities.

[49] Matt Bille, Pat Johnson, Robyn Kane, and Erika R. Lishock, "History and Development of U.S. Small Launch Vehicles," in *To Reach the High Frontier, A History of U.S. Launch Vehicles*, Roger D. Launius and Dennis R. Jenkins, ed. (Lexington, KY: The University Press of Kentucky, 2002), p. 214.

[50] Isakowitz et al., *International Reference Guide to Space Launch Systems,* 3rd ed., p. 279.

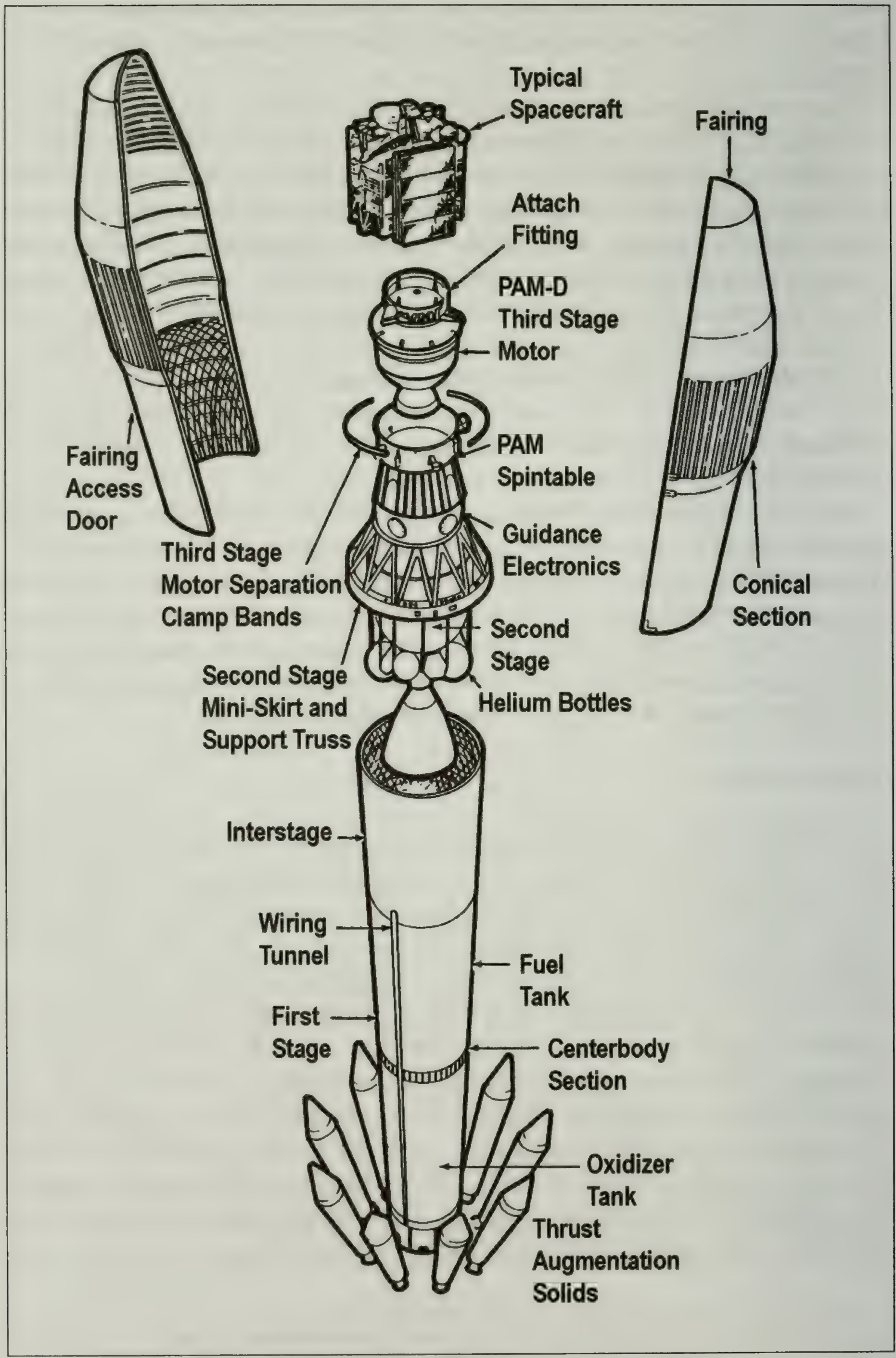
Typical
Spacecraft
Fairing
Attach
Fitting
PAM-D
Third Stage
Motor
Fairing
Access
Door
PAM
Spintable
Guidance
Electronics
Third Stage
Motor Separation
Clamp Bands
Conical
Section
Second
Stage
Second Stage
Mini-Skirt and
Support Truss
Helium Bottles
Interstage
Wiring
Tunnel
Fuel
Tank
First
Stage
Centerbody
Section
Oxidizer
Tank
Thrust
Augmentation
Solids

Figure 2–13. Delta II Components. (The Boeing Company)

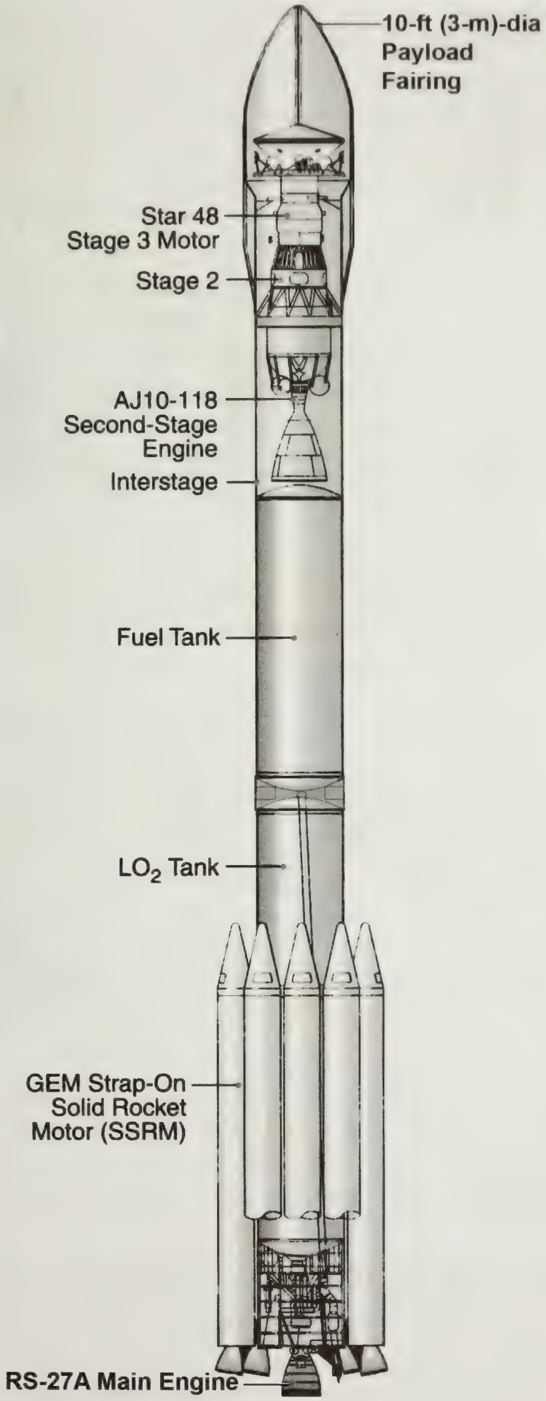
10-ft (3-m)-dia Payload Fairing
Star 48 Stage 3 Motor
Stage 2
AJ10-118 Second-Stage Engine
Interstage
Fuel Tank
LO2 Tank
GEM Strap-On Solid Rocket Motor (SSRM)
RS-27A Main Engine

Figure 2–14. Delta II 7925. (The Boeing Company)

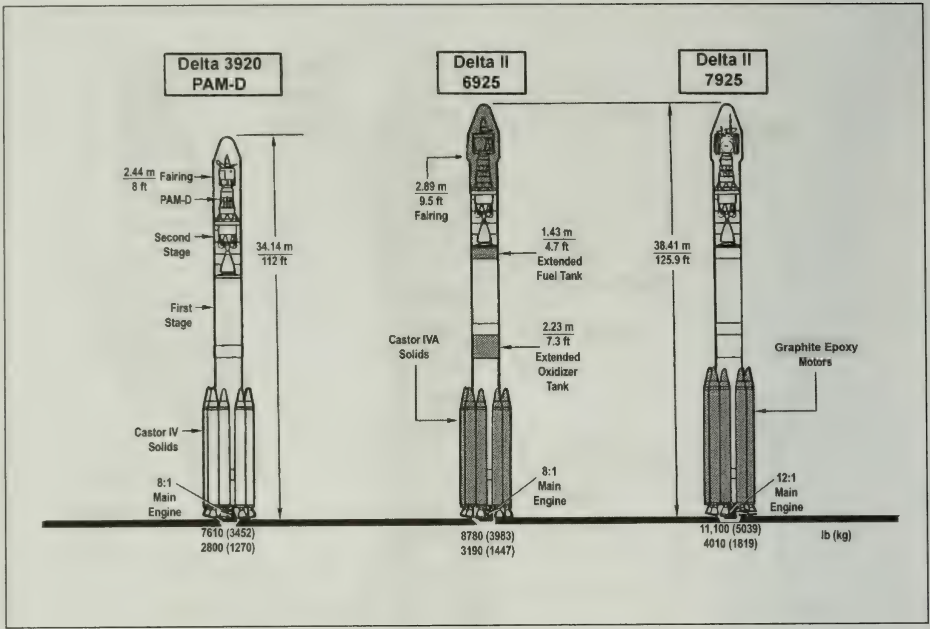
Delta 3920
PAM-D
Delta II
6925
Delta II
7925
2.44 m
8 ft
Fairing
PAM-D
Second Stage
First Stage
34.14 m
112 ft
Castor IV Solids
8:1 Main Engine
7610 (3452)
2800 (1270)
2.89 m
9.5 ft
Fairing
1.43 m
4.7 ft
Extended Fuel Tank
Castor IVA Solids
2.23 m
7.3 ft
Extended Oxidizer Tank
8:1 Main Engine
8780 (3983)
3190 (1447)
38.41 m
125.9 ft
Graphite Epoxy Motors
12:1 Main Engine
11,100 (5039)
4010 (1819)
lb (kg)

Figure 2–15. Delta 3920/PAM-D, Delta II 6925, and Delta II 7925. (The Boeing Company)

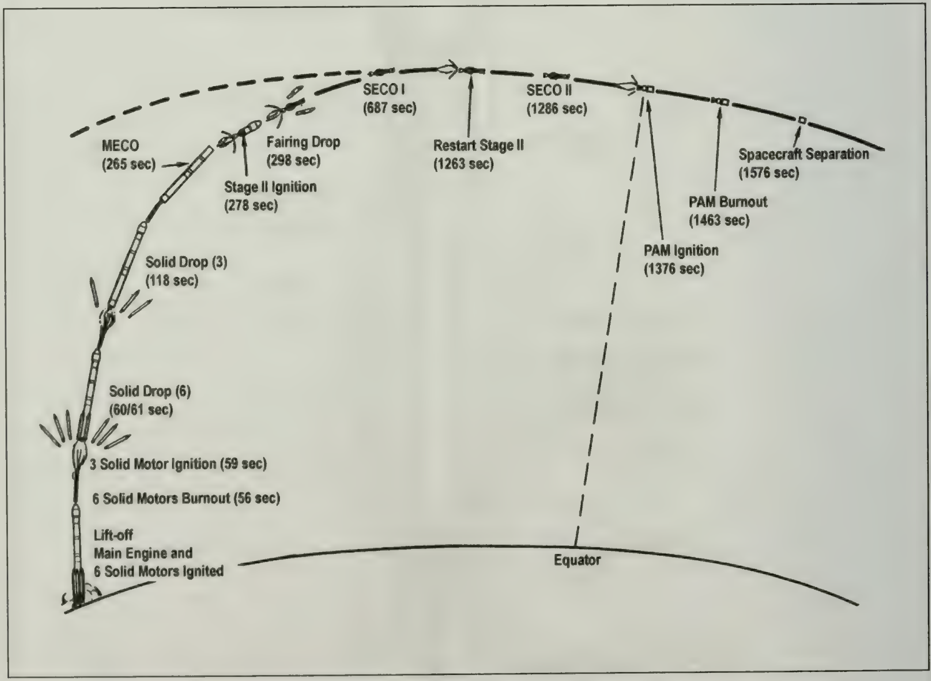
SECO I
(687 sec)
SECO II
(1286 sec)
MECO
(265 sec)
Fairing Drop
(298 sec)
Restart Stage II
(1263 sec)
Spacecraft Separation
(1576 sec)
Stage II Ignition
(278 sec)
PAM Burnout
(1463 sec)
PAM Ignition
(1376 sec)
Solid Drop (3)
(118 sec)
Solid Drop (6)
(60/61 sec)
3 Solid Motor Ignition (59 sec)
6 Solid Motors Burnout (56 sec)
Lift-off
Main Engine and
6 Solid Motors Ignited
Equator

Figure 2–16. Delta II Mission and Launch Sequence Profile for a Typical Geosynchronous Mission. (The Boeing Company)

Orbital established the Pegasus program in 1987. In 1988, the Defense Advanced Research Projects Agency awarded a contract to Orbital for one firm and five options for the rocket. In July 1990, NASA and Orbital Sciences signed an agreement in support of Orbital's commercial launch vehicle programs. This agreement allowed Orbital to enter into sub-agreements with NASA installations in which NASA would provide access to its launch support property and services on a cost-reimbursable basis.[51] In 1991, Goddard Space Flight Center selected the Pegasus to supply Small Expendable Launch Vehicle Services for its Small Explorer program, and on June 4, the Pegasus was chosen for up to 40 more launches under the Air Force Small Launch Vehicle program.[52] The Ballistic Missile Defense Organization awarded another launch contract to Orbital in July 1992. In 1994, NASA selected Orbital for its Ultralight launcher, and Spain selected the Pegasus in October 1994 to launch Minisat 01, the first West European orbital launch.[53] There have been two Pegasus models: the Standard Pegasus, which first flew on April 5, 1990, and the Pegasus XL, which was conceived in 1991 and first flew on June 27, 1994.

The first Pegasus booster rocket was launched on April 5, 1990, from Edwards Air Force Base, California, from underneath NASA's B-52 airplane in a mission originating at Dryden Flight Research Center.[54] Other launches through 1998 took place from the Canary Islands in Spain and Wallops Flight Facility, Virginia, as well as from Edwards and Vandenberg Air Force Bases, both in California, and Cape Canaveral, Florida. The B-52 launched the Pegasus until 1995, when a modified Lockheed L-1011 aircraft, the Orbital "Stargazer," replaced it. The Pegasus XL, an upgraded Pegasus that was longer, heavier, and able to boost larger payloads than the standard Pegasus, used only the L-1011 aircraft. The Pegasus's best-known achievement was its launch of the ORBCOMM communications satellites. Between 1997 and 1999, five Pegasus launches sent 32 satellites into orbit, forming the world's first private, low-Earth orbit communications network.[55] See Table 2–76 for the Pegasus flight history.

Unlike ground-launched rockets, the Pegasus was launched at an altitude of more than 40,000 feet (12,192 meters) from beneath a flying aircraft at an initial speed of Mach 0.8. This air launch offered several advantages. First, because the rocket did not require a launch pad, just a runway from which the aircraft could take off and land, it could be launched from almost anywhere around the world. Second, the booster derived a slight gain in performance (one percent to two percent) from the speed of the carrier aircraft. Third, its trajectory was flatter than the trajectory for ground-launched vehicles, so less power was dissipated in achieving the correct attitude for injection into orbit. Fourth, because the carrier aircraft served the same function as the first stage of a ground-launched vehicle, the rocket itself needed to carry less propellant.[56] Fifth, the fact that the launch took place above 75 percent of Earth's atmosphere reduced the energy needed to reach orbit. Finally, its air launch reduced the amount of stress the launch vehicle faced when compared with ground-launched vehicles.[57] Figure 2–17 shows a Pegasus mated to its B-52 mothership.

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[51] "NASA, Orbital Sciences Corporation Sign Agreement," *NASA News* Release 90-92, July 3, 1990, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1990/90-092.txt* (accessed February 2, 2005).

[52] "Milestones," Orbital, *http://www.orbital.com/About/Milestones/90_99/* (accessed February 2, 2005). Also *Aeronautics and Space Report of the President, Fiscal Year 1991 Activities* (Washington, DC: National Aeronautics and Space Administration, 1992), p. 70; Bille et al., *To Reach the High Frontier, A History of U.S. Launch Vehicles,* p. 216.

[53] Andrew Wilson, ed., *Jane's/Interavia Space Directory, 1999–2000* (Alexandria, VA: 2000), Jane's Information Group (2000), p. 237.

[54] This B-52 was the same aircraft used for the X-15 test flights in the 1960s.

[55] Bille et al., in *To Reach the High Frontier, A History of U.S. Launch Vehicles*, p. 216.

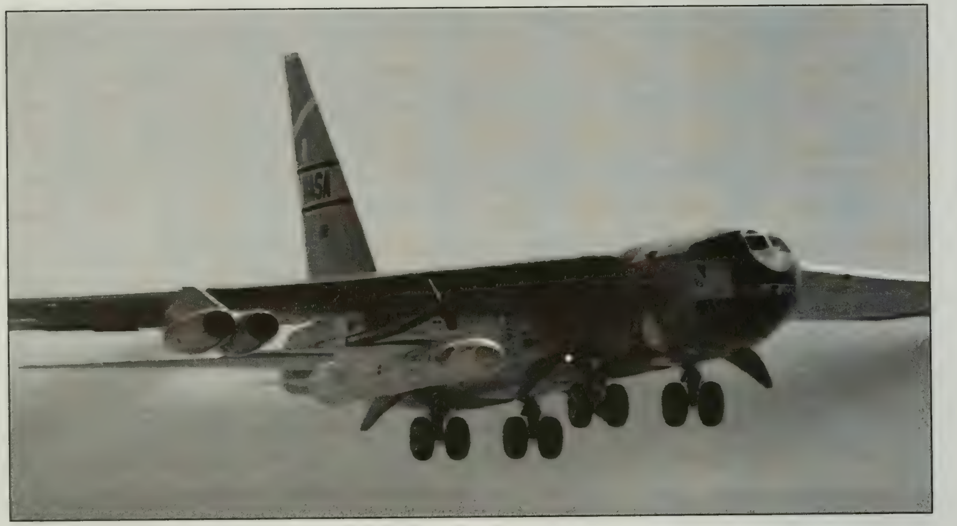

Figure 2–17. Pegasus Mounted Under B-52 Wing. (NASA-DFRC Photo No. EC91-348-3)

A 22-foot (6.7-meter) delta wing mounted on top of Stage 1 provided extra lift. There were three solid rocket motors in its three stages; a payload fairing; an avionics assembly; a lifting wing; an aft skirt assembly, including three movable control fins; and a payload interface system. It also could be equipped with a liquid-propellant fourth stage, the hydrazine auxiliary propulsion system (HAPS), to boost the payload into a higher orbit. The vehicle's blunt payload fairing blended into a cylindrical fuselage and ended in a flared exhaust nozzle. The wing was made of graphite composite structure, and 94 percent of the structural weight of the original model Pegasus was also graphite composite. Three control fins electromechanically actuated provided pitch, roll, and yaw control while the vehicle was still in Earth's atmosphere. When the vehicle reached the upper atmosphere, small rockets mounted in the base of each fin helped control the vehicle. Figure 2–18 shows the Pegasus vehicle.

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[56] "Pegasus Launch Vehicle," Space & Missile Systems Center (AFMC), Department of the Air Force, *http://www.te.plk.af.mil/factsheet/pegfact.html* (accessed February 8, 2005).

[57] Matt Bille et al. in *To Reach the High Frontier, A History of U.S. Launch Vehicles*, p. 215.

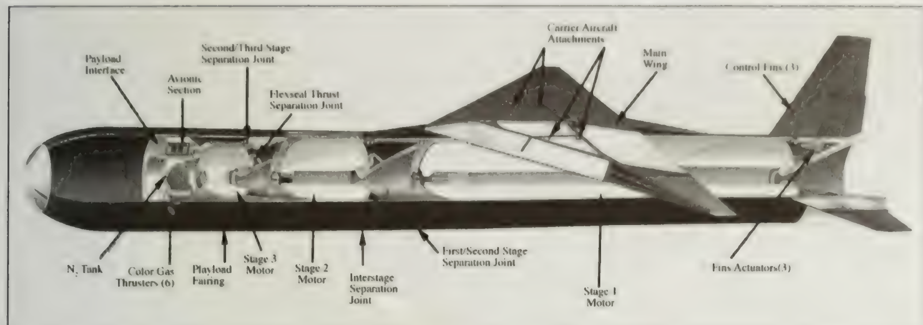
Payload Interface
Second/Third Stage Separation Joint
Avionic Section
Flexseal Thrust Separation Joint
Carrier Aircraft Attachments
Main Wing
Control Fins (3)
N₂ Tank
Color Gas Thrusters (6)
Playload Fairing
Stage 3 Motor
Stage 2 Motor
Interstage Separation Joint
First/Second Stage Separation Joint
Stage 1 Motor
Fins Actuators(3)

Figure 2–18. Pegasus Vehicle. (Orbital Sciences Corp.)

The standard payload fairing consisted of two graphite composite halves with a nosecap bonded to one of the halves and a separation system. The fairing separated when sequentially actuating pyrotechnic devices released the right and left halves of the fairing from a closed position and moved the halves away from either side of the payload. Pegasus could accommodate multiple payloads on the same mission. The standard fairing had a 1.17-meter (3.8-foot) diameter and was 2.13-meters (7-feet) long. If the optional HAPS was used, the fairing was 1.76-meters or 1.79-meters (5.8-feet or 5.9-feet) long. Table 2–77 lists Standard Pegasus characteristics, and Table 2–78 lists Pegasus XL characteristics.

The typical launch sequence begins with release of the Pegasus from the carrier aircraft at an altitude of approximately 11,900 meters (39,000 feet) and a speed of Mach 0.80. Approximately 5 seconds after its drop from the aircraft, when Pegasus had cleared the aircraft, Stage 1 is ignited. The vehicle quickly accelerates to supersonic speed while beginning a pull-up maneuver. Maximum dynamic pressure is experienced about 25 seconds after ignition. At approximately 20 to 25 seconds, a maneuver begins to depress the trajectory, and the vehicle's angle of attack quickly approaches zero.

Stage 1 burnout occurs at approximately 77 seconds, and Stage 2 ignition follows quickly. The payload fairing is jettisoned during Stage 2 burn as quickly as fairing dynamic pressure and payload aerodynamic heating limitations allow, about 110,000 meters (361,000 feet) and 112 seconds after drop from the aircraft. Stage 2 burnout occurs at approximately 168 seconds and is followed by a long coast, during which the payload and Stage 3 achieves orbital altitude. Stage 3 then provides the additional velocity needed to circularize the orbit. Stage 3 burnout typically occurs approximately 10 minutes after launch and 2,200 kilometers (1,200 nautical miles) downrange of the launch point.[58] Figure 2–19 shows the Pegasus XL mission profile.

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[58] *Pegasus User's Guide*, Release 5.0, August 2000 (Orbital Sciences Corporation, 2000), p. 2-1, *http://www.orbital.com/NewsInfo/Publications/peg-user-guide.pdf* (accessed February 4, 2005).

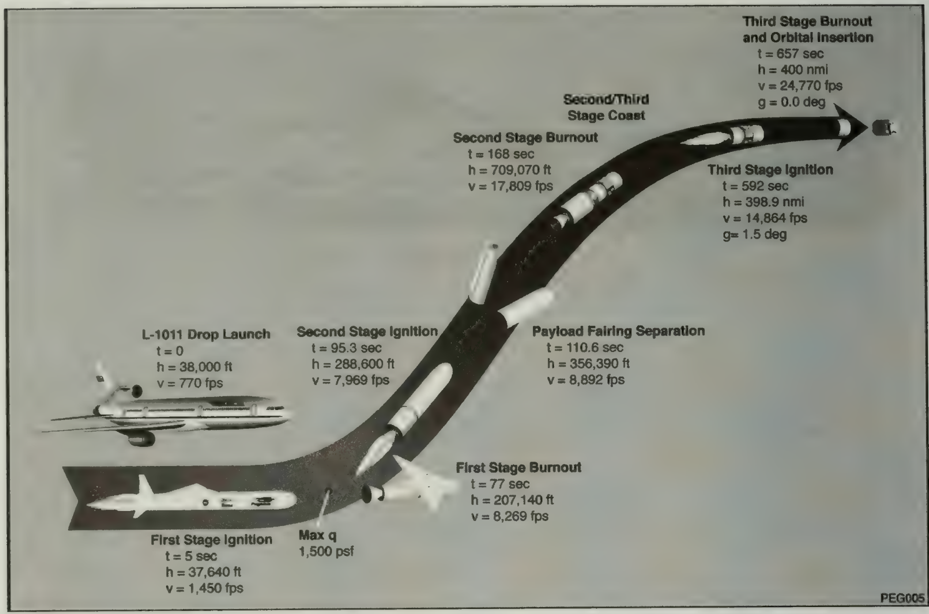
Third Stage Burnout
and Orbital Insertion
t = 657 sec
h = 400 nmi
v = 24,770 fps
g = 0.0 deg
Second/Third
Stage Coast
Second Stage Burnout
t = 168 sec
h = 709,070 ft
v = 17,809 fps
Third Stage Ignition
t = 592 sec
h = 398.9 nmi
v = 14,864 fps
g= 1.5 deg
L-1011 Drop Launch
t = 0
h = 38,000 ft
v = 770 fps
Second Stage Ignition
t = 95.3 sec
h = 288,600 ft
v = 7,969 fps
Payload Fairing Separation
t = 110.6 sec
h = 356,390 ft
v = 8,892 fps
First Stage Burnout
t = 77 sec
h = 207,140 ft
v = 8,269 fps
First Stage Ignition
t = 5 sec
h = 37,640 ft
v = 1,450 fps
Max q
1,500 psf
PEG005

Figure 2–19. Pegasus XL Mission Profile to 741 km (400 nmi) Circular, Polar Orbit with a 227 kg (501 lb) Payload. (Orbital Sciences Corp.)

Scout Launch Vehicle

The standard Scout launch vehicle was a solid propellant, four-stage booster system.[59] It was the world's first all-solid-propellant launch vehicle and one of NASA's most reliable launch vehicles. The Scout was the smallest of the basic NASA launch vehicles. It was used for orbit, probe, and reentry Earth missions. Unlike most of NASA's larger ELVs, the Scout was assembled and the payload integrated and checked-out in the horizontal position. The Scout's first-stage motor was based on an earlier version of the Navy's Polaris missile motor. It's second-stage motor was developed from the Army's Sergeant surface-to-surface missile. The third-stage and fourth-stage motors were adapted by Langley Research Center from the Navy's Vanguard missile.[60] The Scout G1 was the last Scout model. See Table 2–79 for a list of its characteristics.

Since the first Scout launch in 1960, 118 Scout launches had taken place during almost 34 years of service. In the period 1989–1998, six missions successfully launched from Scout ELVs, all from Vandenberg Air Force Base (see Table 2–80). In addition to one NASA payload, Scout also launched DOD payloads. The last Scout launched a military satellite on May 9, 1994. The air-launched Pegasus rocket was considered the operational replacement for the Scout.

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[59] Scout was an acronym for Solid Controlled Orbital Utility Test.

[60] "Scout Launch Vehicle To Retire After 34 Years of Service," *NASA News* Release 94-72, May 6, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-072.txt* (accessed March 22, 2005). Also "Scout–Launch Vehicle," *http://www.vought.com/heritage/special/html/sscout8.html* (accessed November 4, 2005).

Langley Research Center managed the Scout project from its beginning in 1958 until January 1, 1991, when management of the Scout moved to Goddard Space Flight Center. Since 1958, LTV had manufactured the NASA-developed Scout rocket under a series of government contracts that procured flight vehicles in support of NASA science missions. In December 1988, NASA and LTV signed an agreement granting the company exclusive rights to produce and market the Scout commercially. This agreement also enabled LTV to obtain access to and use of Scout launch support facilities at Wallops Flight Facility and at Vandenberg Air Force Base.

Taurus Launch Vehicle

The ground-launched Taurus, developed by Orbital Sciences Corporation, was created by adding the three stages of a Pegasus booster (without the wing and fins) atop a Peacekeeper or Castor 120 first-stage solid-propellant motor referred to as "Stage 0." An aluminum skin and stringer construction interstage extended from the forward skirt of the Castor 120 Stage 0 motor to the aft end of the Stage 1 motor. The lower part of the interstage remained with Stage 0, and the upper part of the interstage flew with the next stage. A field joint between the two sections allowed the Taurus upper stage stack to be mated to the Castor 120 Stage 0 (see Table 2–81 and Figure 2–20).

The Defense Advanced Research Programs Agency (DARPA) contracted with Orbital Sciences in 1989 to build the Taurus rapid response launch vehicle using the Pegasus as a baseline.[61] It was designed for easy transport and as a quick-reaction launch vehicle that could be launched from minimally prepared locations in just a few days.[62] The first Taurus launch took place on March 13, 1994 for a DOD mission. The commercial Taurus, developed after the successful demonstration of the military "ARPA" Taurus, used the Castor 120 first stage rather than the Peacekeeper missile, a slightly larger Orion 50S-G second stage, and a larger fairing.[63] For geosynchronous transfer orbit or deep space missions, the third stage could be replaced by a spin-stabilized Thiokol Star 37 perigee kick motor.

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[61] Wilson, ed., *Jane's/Interavia Space Directory*, p. 240.

[62] "Taurus," *http://space.skyrocket.de/doc_lau/taurus.htm* (accessed February 9, 2005).

[63] "ARPA" Taurus was another name for the military Taurus configuration that used the Peacekeeper first stage. Isakowitz et al., *International Reference Guide to Space Launch Systems*, 3rd ed., p. 437.

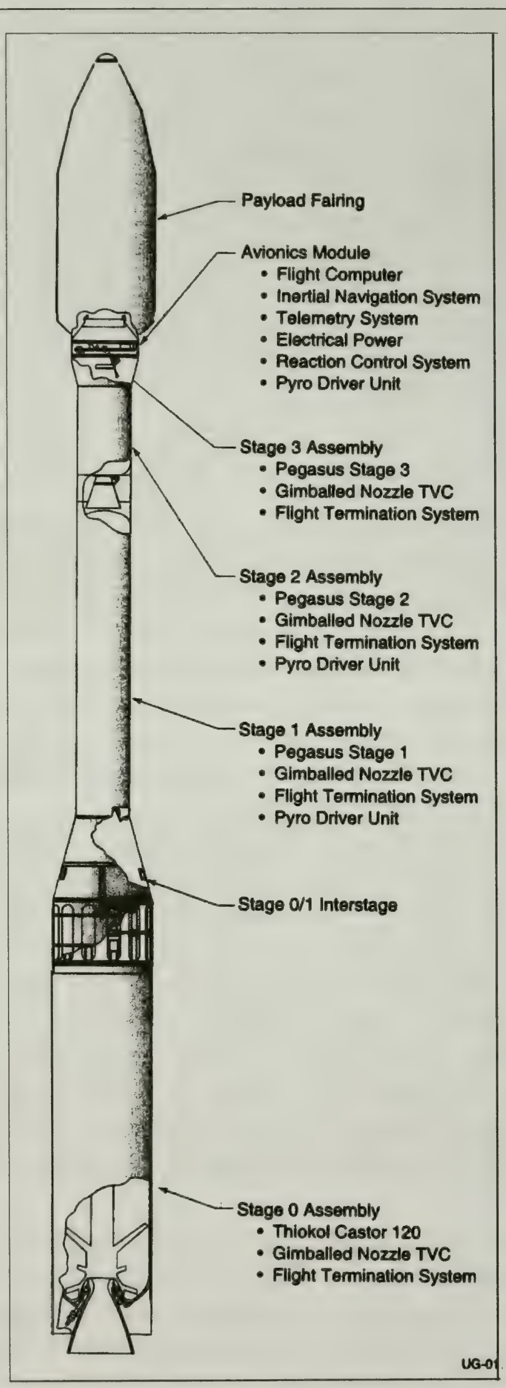
Payload Fairing
Avionics Module
• Flight Computer
• Inertial Navigation System
• Telemetry System
• Electrical Power
• Reaction Control System
• Pyro Driver Unit
Stage 3 Assembly
• Pegasus Stage 3
• Gimballed Nozzle TVC
• Flight Termination System
Stage 2 Assembly
• Pegasus Stage 2
• Gimballed Nozzle TVC
• Flight Termination System
• Pyro Driver Unit
Stage 1 Assembly
• Pegasus Stage 1
• Gimballed Nozzle TVC
• Flight Termination System
• Pyro Driver Unit
Stage 0/1 Interstage
Stage 0 Assembly
• Thiokol Castor 120
• Gimballed Nozzle TVC
• Flight Termination System
UG-01

Figure 2–20. Taurus Launch Vehicle Configuration. (Orbital Sciences Corp.)

The Taurus successfully used payload fairings of 63 inches (160 centimeters) and 92 inches (234 centimeters) diameter to encapsulate the payload. Vermont Composites manufactured the 63-inch fairing, while R-Cubed Composites manufactured the 92-inch fairing. Both were bisector shells constructed of graphite/epoxy facesheets with an aluminum honeycomb core. With the addition of a structural adapter, either fairing could accommodate multiple payloads.

From 1994 through 1998, three Taurus launches took place, all from Vandenberg Air Force Base and with multiple payloads (see Table 2–82).

The Titan Family

From the earliest days of the space program, the U.S. Air Force was the primary user of the Titan, first as an intercontinental ballistic missile and later as a space launch vehicle. With its several configurations and enhanced versions, the Titan launched a wide range of military and civilian spacecraft. For a while in the mid-1980s, DOD prepared to launch its payloads exclusively from the Space Shuttle, and it seemed as if the Titan was reaching the end of its useful life. But some felt that a backup vehicle was needed, and in 1985, the Air Force placed an order with Martin Marietta for 10 launch vehicles called the complementary expendable launch vehicle (CELV) or Titan 34D-7, named for its seven-segment solid motor designed for the earlier, unsuccessful Titan IIIM. To be compatible with Shuttle payload capacity, the Titan payload fairing was increased to 5.1 meters (16.7 feet) in diameter. The 34D-7 included a Centaur upper stage and launched exclusively from Cape Canaveral. After the *Challenger* accident and the removal of DOD payloads from the Space Shuttle, the 34D-7 program grew from 10 to 41 vehicles with a mix of upper stages. The vehicles were renamed the Titan IV, and they would eventually be launched from both West and East Coast launch pads.

The Titan IV was the Nation's largest and most powerful ELV. It provided primary access to space for the heaviest and most important DOD and civil payloads. The first Titan IVA launch occurred successfully on June 14, 1989. Eventually, 22 Titan IVAs were launched, the last in August 1998. Figure 2–21 shows the first stage of the Titan IV ELV used to send NASA's Cassini spacecraft to Saturn.

Even before the first Titan IVA launch, the Air Force began looking for ways to upgrade the Titan. In October 1987, the Air Force awarded Hercules Aerospace a contract for upgraded solid rocket boosters that would have a new propellant formulation, new graphite-composite cases, and hydraulically gimbaled nozzles to replace the system used since the first Titan IIIC. The upgraded Titan motors had three segments rather than seven for greater reliability. This upgrade not only increased payload capability by 25 percent but also used fewer components, resulting in a more reliable Stage 0 booster. This model used a more efficient programmable aerospace ground equipment system to control the vehicle before launch and an improved guidance and control system, based on more accurate and lighter ring gyroscopes, manufactured by Honeywell. Mechanical and electrical interfaces to the payload were also standardized, and the design of the core vehicle could be fitted with various kits to adapt to specific payloads. Production processes were redeveloped to use a "factory-to-launch" approach. The goal was to deliver problem-free hardware requiring a minimal amount of launch site assembly and reserving the launch site for final stacking, checkout, countdown, and launch.

Development of the new motors took longer than expected, however, partly because of an explosion during the first test firing. The first flight of the new Titan IV with its new motors, now designated Titan IVB, did not occur until February 23, 1997. The new Titan IV stood 61 meters (200 feet) tall and had a lift capability of 21,680 kilograms (47,796 pounds) to low-Earth orbit and 5,760 kilograms (12,700 pounds) to geosynchronous orbit. Lockheed Martin provided overall program management, system integration, and payload integration for the program. It also built the first and second stages and the Centaur upper stage.[64]

The Air Force found a use, too, for old Titan II ICBMs. As the technology for nuclear deterrence changed, the Air Force began in July 1982 to deactivate its Titan II missiles, removing its last ICBM from its silo in Arkansas on June 23, 1987. In January 1986, the Air Force decided to begin converting some of its deactivated Titan II ICBMs for use as medium-lift space launch vehicles. From its fleet of 54 deactivated Titan IIs, the Air Force selected Martin Marietta to modify 14 for space launches from Vandenberg Air Force Base into polar orbit. Modification entailed replacing the core vehicle's warhead interface with a space payload interface and a 3-meter (9.8-foot) payload fairing and upgrading the electronics, avionics, and guidance systems using Titan III technology. An attitude control system was added for stabilization during the coast phase after second-stage shutdown and before payload separation.[65] Used for launches into polar orbit, the space launch complex at Vandenberg Air Force Base was also modified. The resulting Titan II space launch vehicle was a two-stage, liquid-fueled booster designed to provide a small-to-medium weight class capability. It could lift approximately 4,200 pounds (1,905 kilograms) into polar low-Earth circular orbit.[66] The first launch of a Titan II 23G space launch vehicle took place on September 5, 1988, from Vandenberg Air Force Base when it sent a classified payload into low-Earth orbit.

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[64] Isakowitz et al., *International Reference Guide to Space Launch Systems*, 3rd ed., p. 470. Also "Titan," Lockheed Martin, *http://www.lockheedmartin.com/wms/findPage.do?dsp=fec&ci=15525&rsbci=13181&fti=0&ti=0&sc=400* (accessed December 14, 2004).

[65] Art Falconer, "Epic Proportion: The Titan Launch Vehicle," *Crosslink* (Aerospace Corporation, Winter 2002/2003): 35 (NASA History Office Folder 16680). Also Isakowitz et al., *International Reference Guide to Space Launch Systems*, 3rd ed., p. 470.

[66] "Titan II Space Launch Vehicle," Lockheed Martin (NASA History Office Folder 16680).

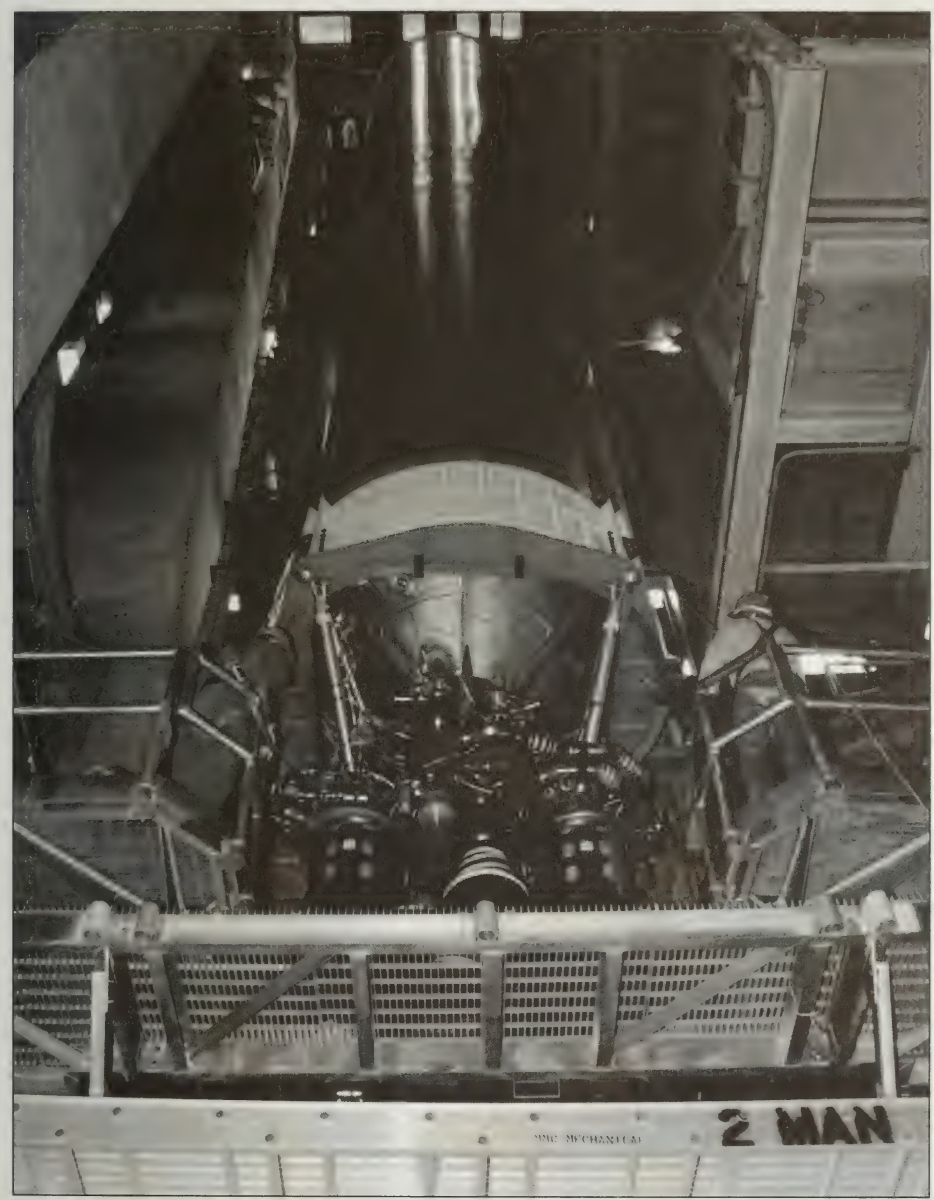

Figure 2–21. The first stage of the Titan IV ELV that sent NASA's Cassini Spacecraft to Saturn and its moon. Titan is lowered into a high bay in the Vertical Integration Building at Cape Canaveral Air Station to begin stacking operations, April 14, 1997. (NASA Photo No. KSC-97PC-640)

During 1989–1998, the Titan launched only a few civilian spacecraft. All but one were converted Titan ICBMs; the final nonmilitary Titan payload during this decade launched NASA's Cassini spacecraft to Saturn on a new Titan IVB Centaur. Table 2–83 lists all Titan launches during this period. Table 2–84 lists Titan II characteristics.

The Space Shuttle

By 1989, regular Space Shuttle flights had resumed, and 66 Shuttle flights took place in the decade from 1989–1998. Because NASA policy dictated that the Space Shuttle could be used for launches only when a human presence was required or when an ELV was not appropriate to deploy a payload, more on-board science missions took place and the Shuttle deployed fewer payloads than in the years before the *Challenger* accident. Among the Shuttle payloads were some of the most important space science projects, including the Hubble Space Telescope, the Galileo spacecraft, and the Gamma Ray Observatory.

A new orbiter, the *Endeavour*, joined the fleet of *Discovery*, *Columbia*, and *Atlantis* and began flight operations on May 7, 1992, when it blasted off on the STS-49 Intelsat VI repair mission. Table 2–85 lists all Space Shuttle missions from 1989 to 1998

In 1995, the Space Shuttle program demonstrated a new capability. In preparation for construction of the International Space Station, the crews of the Space Shuttle carried out a series of docking missions with the Russian Space Station *Mir*. U.S. astronauts lived aboard *Mir*, sometimes for several months at a time, while they acclimated themselves to living and working in space. At the end of the decade, the first Space Station mission took place when STS-88 sent materials for construction of the Station.

In November 1995, in an effort to reduce costs and increase efficiency, NASA announced its intention to pursue a non-competitive contract with the United Space Alliance (USA) that would consolidate contracts for Space Shuttle processing and operations in a single contract. USA was a joint venture between Rockwell International and Lockheed Martin Corporation. Together, these two companies held 69 percent of the dollar value of all Shuttle-related prime contracts. The consolidation virtually ensured that NASA would negotiate with the new company.[67] In April 1996, NASA signed two agreements designating USA the prime contractor for Shuttle processing work performed by Lockheed at Kennedy Space Center and Shuttle operations work performed by Rockwell at Johnson Space Center.

In September 1996, NASA entered into a contract with USA as the prime contractor for Space Shuttle and International Space Station activities to ensure that all NASA missions were successfully accomplished according to the applicable flight definition and requirements, schedule, and implementation plan. The original six-year contract ran from October 1996 through September 2002 and consisted of two phases for consolidating the existing prime contracts. During the first phase, USA assumed overall responsibility for the fleet of orbiters. During the second phase, which began in September 1997, the contracts for Kennedy Space Center base operations, the waste collection system, flight software, flight equipment, and solid rocket boosters were consolidated in the USA contract. As of early 2000, the remaining prime contracts—external tanks, Space Shuttle main engines, and reusable solid rocket motors—remained to be consolidated.[68]

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[67] "NASA To Pursue Non-Competitive Shuttle Contract With U.S. Alliance," *NASA News* Release 95-205, November 7, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-205.txt* (accessed April 17, 2005).

Space Shuttle Characteristics

The Space Shuttle that NASA flew in the decade beginning in 1998 consisted of four primary elements: an orbiter spacecraft, two SRBs, an external tank to house fuel and an oxidizer, and three Space Shuttle main engines (SSMEs). Rockwell International built the orbiters. Rockwell's Rocketdyne Division built the main engines.[69]

Thiokol Corporation produced the SRB motors/ Martin Marietta Corporation built the external tank. Johnson Space Center directed the orbiter and integration contracts, while Marshall Space Flight Center managed the solid rocket booster, external tank, and Space Shuttle main engine contracts.[70] Rockwell also was the contractor for Space Shuttle operations at Johnson Space Center that included maintenance and operation of Space Shuttle facilities, flight preparation, and sustained engineering support. Lockheed Martin was responsible for Shuttle processing at Kennedy Space Center.

External Tank

The external tank held the liquid hydrogen fuel and liquid oxygen oxidizer in separate pressurized tanks and supplied them under pressure to the three main engines in the orbiter during liftoff and ascent. The main engines consumed approximately 64,000 gallons (242,266 liters) of fuel each minute. When the main engines were shut down, the external tank was jettisoned into Earth's atmosphere where it broke up and fell into a remote ocean area. The external tank was not recovered. When loaded with fuel, the external tank was the largest and heaviest element of the Space Shuttle. Built from aluminum, it also acted as the backbone for the orbiter and solid rocket boosters. The external tank was composed of three major components: the forward liquid oxygen tank, an unpressurized intertank containing most of the electrical components, and the aft liquid hydrogen tank. Characteristics of the external tank are shown in Table 2–86. Figure 2–22 shows a cutaway drawing.

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[68] NASA Office of Inspector General, *Audit Report: Space Flight Operations Contract Phase II–Cost-Benefit Analysis*, IG-00-015, National Aeronautics and Space Administration (March 14, 2000), pp. 1–2.

[69] In December 1996, Boeing purchased the Space and Defense divisions of Rockwell International and renamed them Boeing North American. Rocketdyne had been part of Rockwell when the SSME contract was awarded. It was bought by Boeing in December 1996 when Boeing bought Rockwell. Rocketdyne became the Rocketdyne Division of Boeing North American.

[70] Detailed descriptions of all Space Shuttle components can be found in the *NSTS 1988 News Reference Manual*, September 1988, at *http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/stsref-toc.html#srb-recovery* (accessed February 25, 2005) and in the *Shuttle Crew Operations Manual*, SFOC-FL0884, Rev. B, CPN-3, January 13, 2003. See also a summary in Judy Rumerman, compiler, *NASA Historical Data Book, 1979–1988, Volume V* (Washington, DC: National Aeronautics and Space Administration Special Publication 4012, 1999), pp. 33–47 and pp. 123–147. Also available at *http://history.nasa.gov/SP-4012/vol5/cover5.html*.

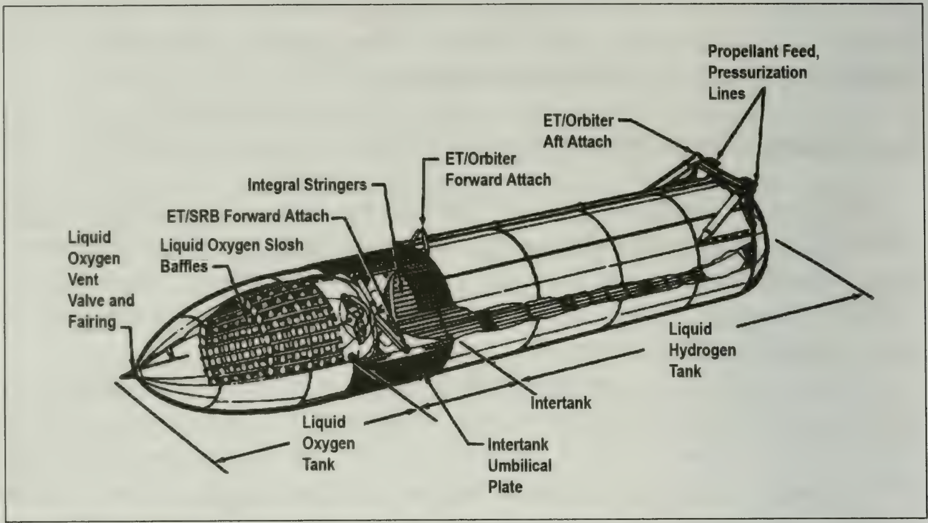
Propellant Feed, Pressurization Lines
ET/Orbiter Aft Attach
ET/Orbiter Forward Attach
Integral Stringers
ET/SRB Forward Attach
Liquid Oxygen Vent Valve and Fairing
Liquid Oxygen Slosh Baffles
Liquid Hydrogen Tank
Intertank
Liquid Oxygen Tank
Intertank Umbilical Plate

Figure 2–22. Drawing of Space Shuttle External Tank. (NASA)

Solid Rocket Booster

The solid rocket boosters were the largest solid-propellant motors ever flown and the first designed for refurbishment and reuse. The two boosters provided the main thrust to lift the Space Shuttle up off the launch pad to an altitude of about 150,000 feet (45.7 kilometers) or 24 nautical miles. The two solid rocket boosters carried the entire weight of the external tank and orbiter and transmitted the weight load through their structure to the mobile launcher platform. The solid rocket boosters were ignited after the thrust levels of the three main engines were verified. During flight, the solid rocket booster nozzles swiveled up to 6 degrees, redirecting the thrust and steering the Shuttle toward orbit. Seventy-five seconds after booster separation, SRB apogee occurred at an altitude of approximately 220,000 feet (67 kilometers) or 35 nautical miles. Impact in the Atlantic Ocean occurred approximately 122 nautical miles (226 kilometers) downrange. Table 2–87 lists solid rocket booster characteristics. Figure 2–23 shows an exploded view.

Space Shuttle Main Engine

The three Space Shuttle main engines were clustered at the tail end of the orbiter. These high-performance liquid-propellant engines were the world's first reusable rocket engines with each designed to operate for 7.5 hours over a lifespan of 55 starts. They operated with variable thrust levels in a staged combustion cycle. The engines burned liquid hydrogen as the propellant fuel and liquid oxygen as the oxidizer in a 6:1 ratio. The propellant was carried in separate tanks in the external tank and supplied to the main engines under pressure. The main engines could be throttled over a range of 65 percent to

109 percent of their rated power level in 1 percent increments. A value of 100 percent thrust corresponded to a thrust level of 375,000 pounds (1,668 kilonewtons) at sea level and 470,000 pounds (2,091.7 kilonewtons) in a vacuum. A thrust value of 104 percent (called full power) was typically used at launch, although each engine could be throttled to its maximum of 109 percent if necessary. (This power level has never been used on a Shuttle flight). All three engines received the same throttle command at the same time, normally from the orbiter general-purpose computers, although manual control of engine throttling was possible during certain contingency situations.

Firing of the three main engines began 6.6 seconds before launch. The three engines were fired at intervals of 120 milliseconds. If all three engines failed to reach at least 90 percent thrust over the next 3 seconds, a main engine cutoff command was issued automatically, followed by cutoff of all three engines. If launch proceeded normally, the engines were throttled back about 26 seconds after launch to protect the Shuttle from aerodynamic stress and excessive heating. The engines returned to full power about 60 seconds after launch and typically continued at full power for about 8.5 minutes until shortly before the Shuttle entered orbit. At about 7 minutes, 40 seconds after launch, the engines were throttled down so the vehicle and crew were not subject to forces more than 3g. The main engines operated in parallel with the solid rocket boosters during the initial ascent. After the boosters separated, the main engines continued to operate. During ascent, each engine could be gimbaled plus or minus 10.5 degrees around the yaw and pitch axes to help steer the Shuttle.[71]

The Shuttle's main engines were upgraded twice during this decade. The Block 1 SSMEs first flew on STS-70 on July 13, 1995. These engines used a new high-pressure liquid oxidizer turbopump that increased safety margins and the reliability of the Shuttle's main engines. In 1998, the Block IIA SSMEs were first used on STS-95. These upgrades increased safety and reliability and simplified manufacturing and maintenance.[72] The design had a larger nozzle throat that resulted in decreased operating pressure and temperature. To achieve the same performance as the earlier engines, the Block IIA engines typically operated at 104.5 percent thrust at launch. Figure 2–24 shows the SSME components. Table 2–88 lists SSME characteristics.

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[71] David Darling, "Space Shuttle," *The Encyclopedia of Astrobiology, Astronomy, and Spaceflight, http://www.daviddarling.info/encyclopedia/S/Space_Shuttle.html* (accessed February 28, 2005).

[72] Susie Unkeless, Jack Vautin, Boeing Rocketdyne, telephone conversation, February 28, 2005. Also "STS-95 Space Shuttle Mission Chronology," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-95.htm* (accessed February 28, 2005).

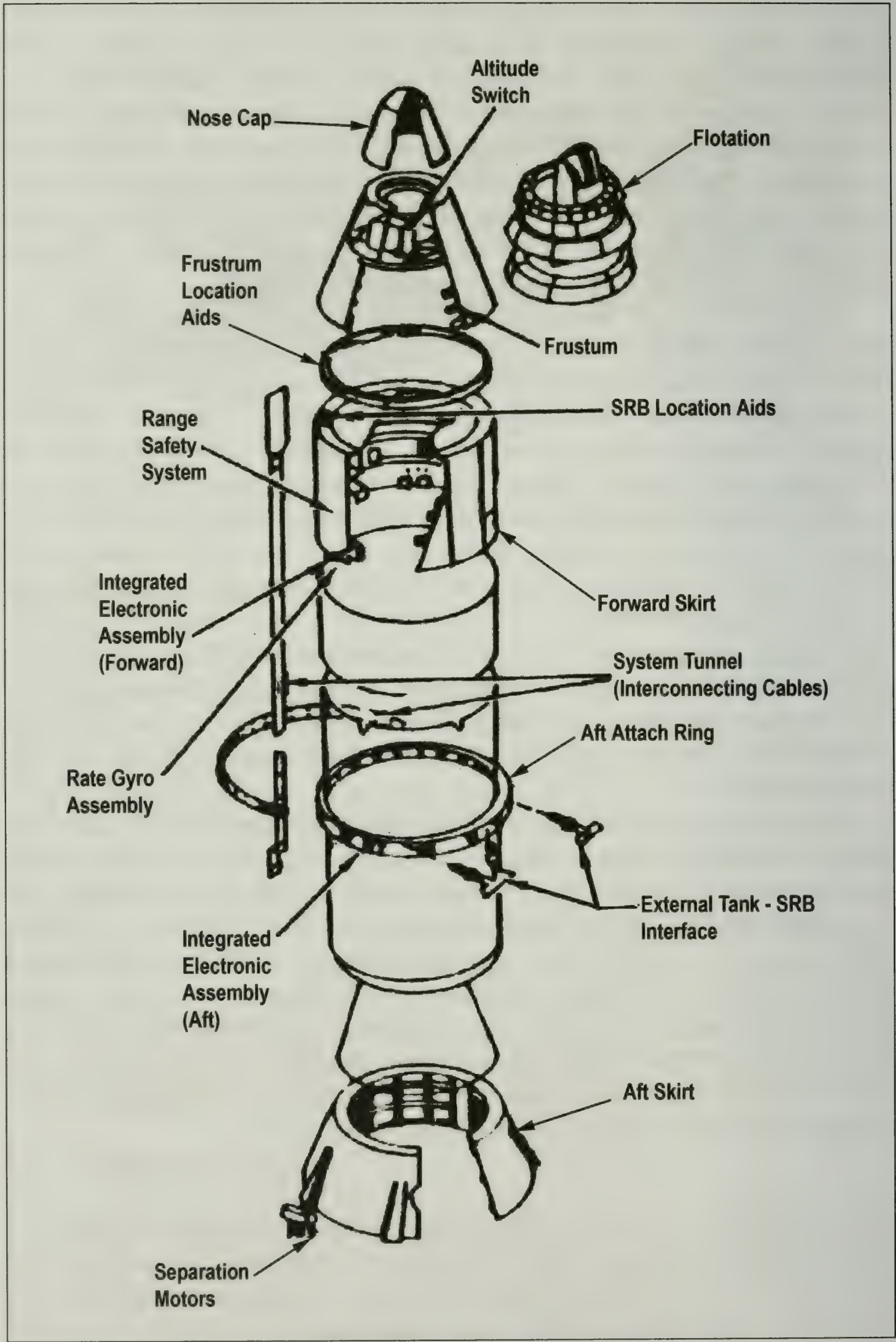
Altitude Switch
Nose Cap
Flotation
Frustrum Location Aids
Frustum
SRB Location Aids
Range Safety System
Integrated Electronic Assembly (Forward)
Forward Skirt
System Tunnel (Interconnecting Cables)
Aft Attach Ring
Rate Gyro Assembly
External Tank - SRB Interface
Integrated Electronic Assembly (Aft)
Aft Skirt
Separation Motors

Figure 2–23. Exploded View of Space Shuttle Solid Rocket Booster.

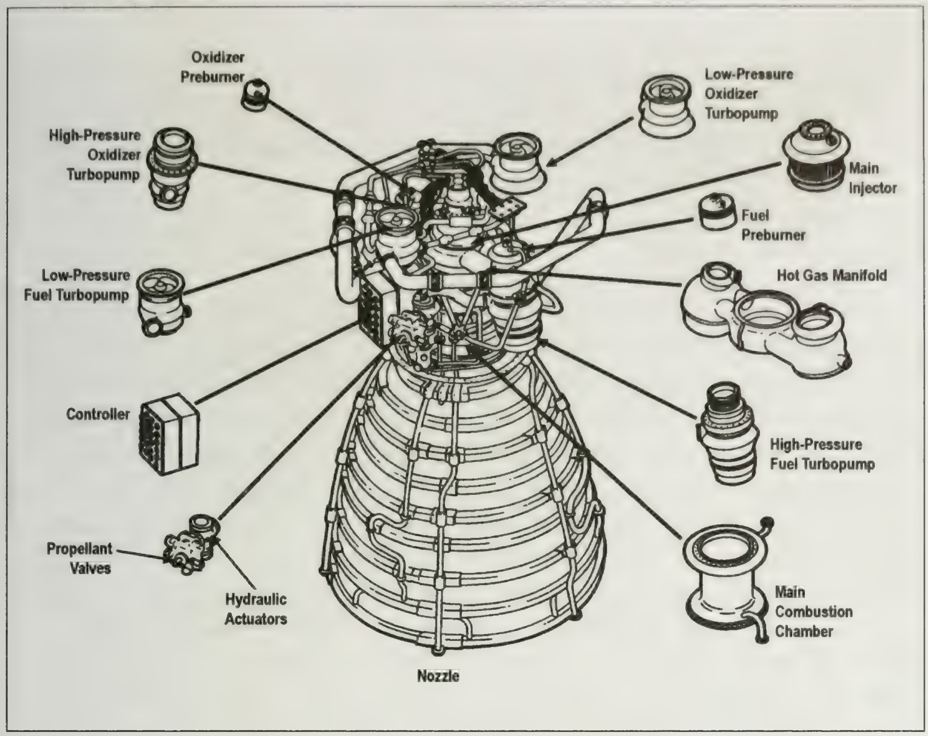
Oxidizer Preburner
High-Pressure Oxidizer Turbopump
Low-Pressure Fuel Turbopump
Controller
Propellant Valves
Hydraulic Actuators
Nozzle
Low-Pressure Oxidizer Turbopump
Main Injector
Fuel Preburner
Hot Gas Manifold
High-Pressure Fuel Turbopump
Main Combustion Chamber

Figure 2–24. Space Shuttle Main Engine Components. (Rocketdyne)

Two orbital maneuvering system engines, mounted on either side of the upper aft orbiter fuselage, provided thrust for major orbital changes. For more precise motions in orbit, 44 small rocket engines, clustered on the Shuttle's nose and on either side of the tail, were used. Together, they were known as the reaction control system and helped Shuttle astronauts retrieve, launch, and repair satellites in orbit.

Launch and Operations

All Space Shuttle missions launched from Kennedy Space Center. The majority also landed there although, during this decade, about 39 percent landed at Edwards Air Force Base in California. See the individual Shuttle mission tables in chapter 3 for specific launch and landing information.

All satellites released from a Space Shuttle initially entered low-Earth orbit. Some remained in that orbit throughout their working lives. Many spacecraft, however, operated in geosynchronous orbit, approximately 35,790 kilometers (19,325 nautical miles or 22,300 miles) above Earth and aligned with the equator, with a speed in orbit that matched the speed of Earth's surface below. Spacecraft reached this altitude by firing an upper stage, an attached propulsion unit such as an IUS or PAM, after deployment from the Shuttle orbiter. Interplanetary explorers launched from the Space Shuttle also used an IUS. They left low-Earth orbit on trajectories that sent them out into our solar system and beyond.

Upper Stages

Upper stages were used to boost ELV and Shuttle payloads from a low-Earth orbit to geostationary transfer orbit, geosynchronous orbit, or into an interplanetary trajectory. During 1989 to 1998, NASA used three types of upper stages: the PAM, the Centaur Upper Stage, and the IUS.

Payload Assist Module

The PAM was designed to boost satellites deployed in low-Earth orbit into a higher operational orbit. Different types of PAMs were used depending on the weight of the satellite it needed to boost. A special PAM, known as PAM-D, was adapted for use with Delta launch vehicles. The PAM-DII was designed to boost Shuttle payloads into an elliptical transfer orbit after a satellite was deployed from the Shuttle's cargo bay. A specially designed PAM-S was used on the Ulysses mission for the first time in combination with an IUS to propel the spacecraft toward Jupiter. The PAM's expendable stage consisted of a spin-stabilized, solid-fueled rocket motor; a payload attach fitting to mate with the satellite; and timing, sequencing, power, and control assemblies.[73] The first launch of the PAM as the top stage of a Delta took place in 1980. The PAM made its debut flight from the Space Shuttle in 1982. Figure 2–25 shows the Ulysses spacecraft with the PAM and IUS.

Centaur Upper Stage

The Centaur was a powerful, liquid-propellant rocket—this country's first high-energy, upper-stage launch vehicle. It was developed under the direction of Lewis Research Center in the 1960s and assembled by General Dynamics. It used a liquid hydrogen-liquid oxygen propellant combination in two restartable Pratt & Whitney RL10 engines that produced more thrust for each pound of propellant burned per second than rockets using only kerosene-based hydrocarbon fuels (see Figure 2–26). The rocket was first developed to be used with the Atlas ELV, and in the decade from 1989–1998, was used on almost all Atlas launches. In the 1970s, the Centaur had been combined with the Titan III to launch larger spacecraft. Later, NASA had planned to use the Centaur to boost Shuttle payloads into higher orbits. But with the increased emphasis on safety following the *Challenger* accident, NASA determined that even with modifications, it was too dangerous to carry a liquid-propellant rocket inside a crewed spacecraft. In June 1986, the Shuttle/Centaur program was cancelled, eliminating the Centaur for use on the Shuttle.

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[73] "Space Transportation System Payloads: Payload Assist Module," *http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/carriers.html* (accessed March 17, 2005).

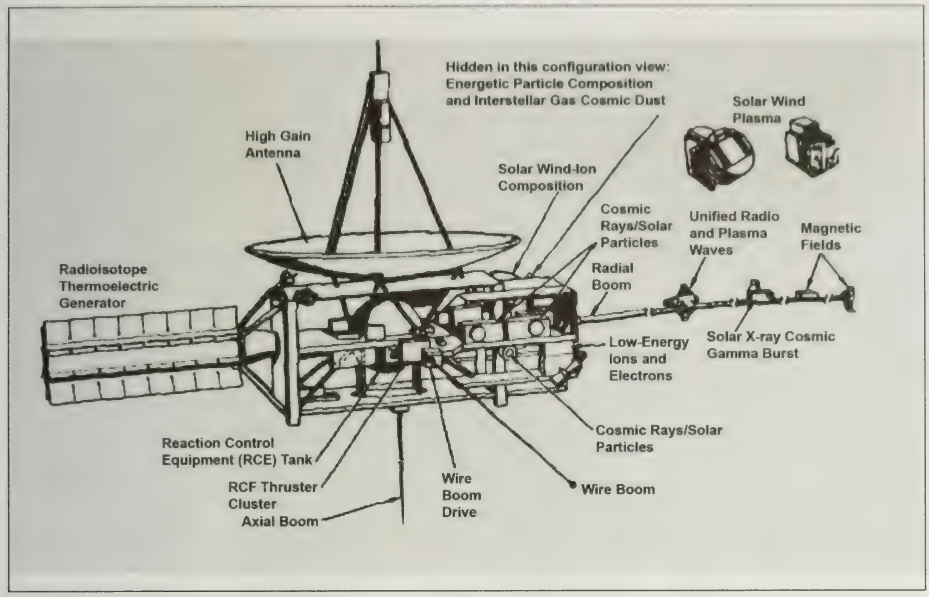
Hidden in this configuration view:
Energetic Particle Composition and Interstellar Gas Cosmic Dust
Solar Wind Plasma
High Gain Antenna
Solar Wind-Ion Composition
Cosmic Rays/Solar Particles
Unified Radio and Plasma Waves
Magnetic Fields
Radioisotope Thermoelectric Generator
Radial Boom
Low-Energy Ions and Electrons
Solar X-ray Cosmic Gamma Burst
Cosmic Rays/Solar Particles
Reaction Control Equipment (RCE) Tank
RCF Thruster Cluster
Axial Boom
Wire Boom Drive
Wire Boom

Figure 2–25. Ulysses Sits atop the Payload Assist Module-S and IUS Combination in the Vertical Processing Facility at Kennedy Space Center. (NASA/JPL-Caltech)

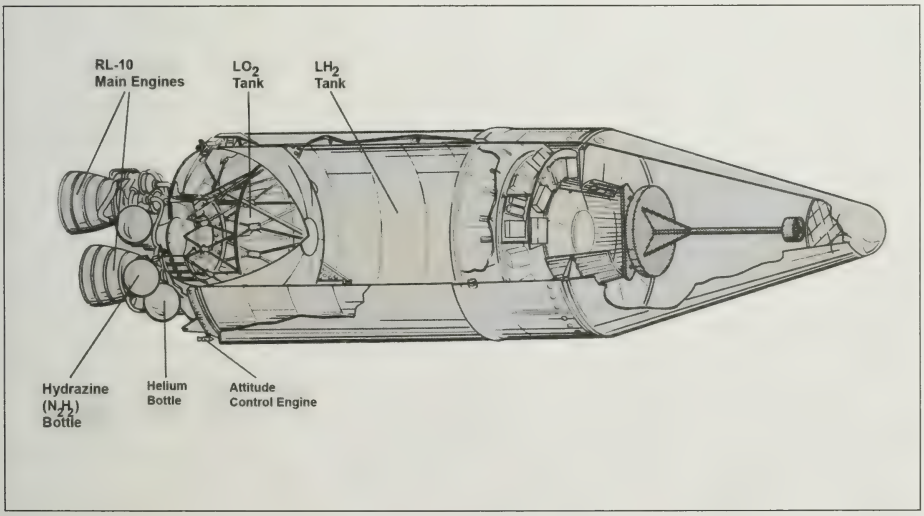
RL-10 Main Engines
LO$_2$ Tank
LH$_2$ Tank
Hydrazine (N_2H_2) Bottle
Helium Bottle
Attitude Control Engine

Figure 2–26. Pratt & Whitney RL10 Engine used on the Centaur Upper Stage. (Pratt & Whitney)

In the wake of the *Challenger* accident, the country's space program returned to using ELVs for all missions suitable for those launchers, and attention focused on improving the Centaur for use as an ELV upper stage. As General Dynamics began developing new Atlas launch vehicles in the late 1980s, it also improved the Centaur as its "engineers dusted off NASA studies for Centaur improvements never implemented . . . ." A pressure-fed system replaced its boost pumps, reducing complexity and cost, and its avionics system was upgraded. Designers developed a new 14-foot (4.3-meter)-diameter metal nose fairing to accommodate larger payloads. A computer-controlled pressurization system with redundant sensors was adopted, making the system more versatile and reliable.[74] This updated Centaur was first used on July 25, 1990, for the Atlas I launch of the Combined Release and Radiation Effects Satellite. See Figure 2–27 for a diagram of the Atlas-Centaur upper stage.

The Centaur G model, originally developed for launching Shuttle payloads, was updated for use on the Titan IV. Martin Marietta delivered the first Titan IV Centaur in December 1990. It had a bare metal tank, like that of the Atlas Centaur. However, the upper fuel tank was stretched to 5 meters (16.4 feet) in diameter. Most Titan IV Centaurs were used for classified DOD payloads. However, one model launched the Cassini/Huygens probe for NASA on an interplanetary trajectory in October 1997. Characteristics of the Titan Centaur are given in Table 2–89.

Inertial Upper Stage

The two-stage, solid-fueled IUS delivered a satellite to a high-stage operational orbit or to an escape trajectory for an interplanetary mission from low-Earth orbit. It extended the reach of the Space Shuttle and was also used with the Titan launch vehicle, particularly the Titan 34D and Titan IV. The IUS had two solid rocket motors, an aft skirt, an interstage, and an equipment support section where the avionics were located. It could lift 5,000 pounds (2,268 kilograms) from low-Earth to geosynchronous orbit. Figure 2–28 shows an IUS being attached to the Magellan spacecraft, which launched from STS-30 in 1989.

In a typical Titan IV-IUS launch into geosynchronous orbit, the IUS separated from the Titan's second-stage booster approximately 9 minutes after launch. Then, for the next 6 hours, 54 minutes, the IUS autonomously performed all functions to place the payload into its proper orbit. The first IUS rocket burn, which placed the payload into geosynchronous transfer orbit, occurred a little more than 1 hour into the IUS booster flight. The IUS second solid rocket motor ignited about 6.5 hours into the flight, followed by a coast phase, and then separation of the payload from the IUS after placing it into geosynchronous orbit.

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[74] Virginia P. Dawson and Mark D. Bowles, *Taming Liquid Hydrogen: The Centaur Upper Stage Rocket, 1958-2002* (Washington, DC: National Aeronautics and Space Administration Special Publication-2004-4230, 2004), pp. 242–243.

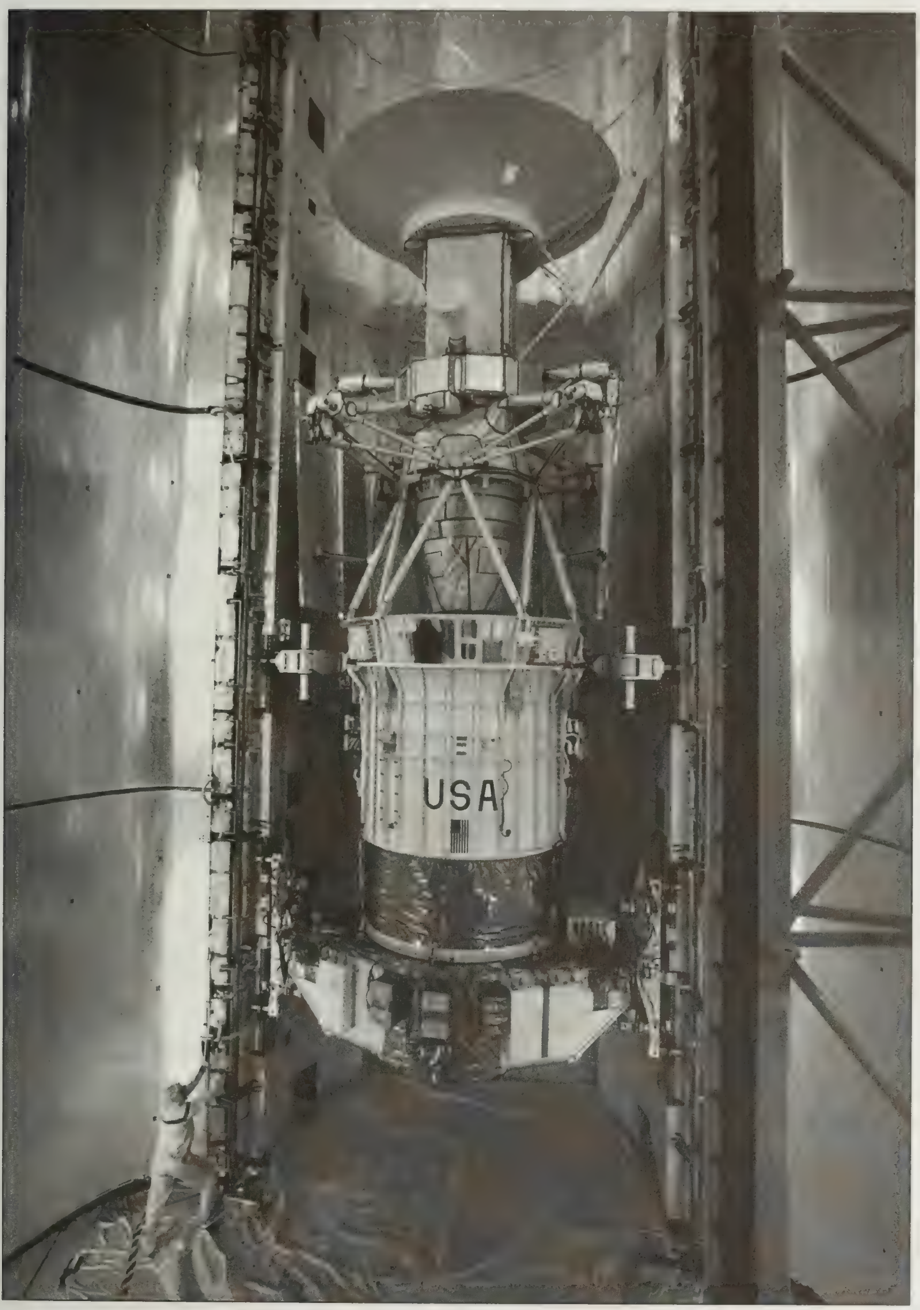

Figure 2–27. Atlas-Centaur Upper Stage. (NASA-GRC Photo No. C-1998-02814)

In a typical Shuttle-IUS launch to geosynchronous orbit, after reaching low-Earth orbit, the Shuttle opened its payload doors and the IUS tilted outward, extending the IUS and its payload into space. After satellite and IUS checkout, the Shuttle astronauts ejected the IUS and its cargo from the orbiter. The IUS onboard computers then directed a series of maneuvers and fired the first-stage motor for approximately 140 seconds to propel the IUS and spacecraft toward the desired geosynchronous position. After a coast period of several hours, the second-stage motor ignited and burned for approximately 100 seconds, injecting the IUS into a final circularized orbit. The IUS then separated from the satellite and moved to a position where it neither collided with nor contaminated the satellite.[75] Table 2–90 lists IUS characteristics. Table 2–91 lists missions using an IUS.

Advanced Programs and Projects

Advanced Programs conducted studies and selected development efforts to support potential new programs, system improvements, and expanded capabilities for space transportation systems. The objectives were to increase reliability, cost effectiveness, and capability of spaceflight systems; continue enhancing crew safety for the Space Shuttle and Space Station; implement flight and ground systems improvements to substantially reduce the cost of spaceflight operations; and pursue technology developments to meet future human spaceflight requirements. Development efforts focused on advanced transportation, advanced operations, and satellite servicing. The two program elements were advanced operations and advanced space systems.

Tethered Satellite System

The Tethered Satellite System (TSS) program was a cooperative effort between the government of Italy and NASA. The TSS program was to enable science to be performed in the upper atmosphere and ionosphere from a satellite connected to the Space Shuttle by means of a tether up to 100-kilometers (62-miles) long. The effect of the tether passing through space also was expected to generate an electric current that could be conducted to the orbiter.

The first attempt at performing the TSS experiment took place on STS-46, launched on July 31, 1992. Due to problems with the deployment mechanism, the *Atlantis* crew could deploy the tethered satellite only 256 meters (840 feet) instead of the goal of 20 kilometers (12.4 miles).

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[75] "Inertial Upper Stage: IUS Team," Boeing, *http://www.boeing.com/defense-space/space/ius/ius_team.htm* (accessed March 18, 2005).

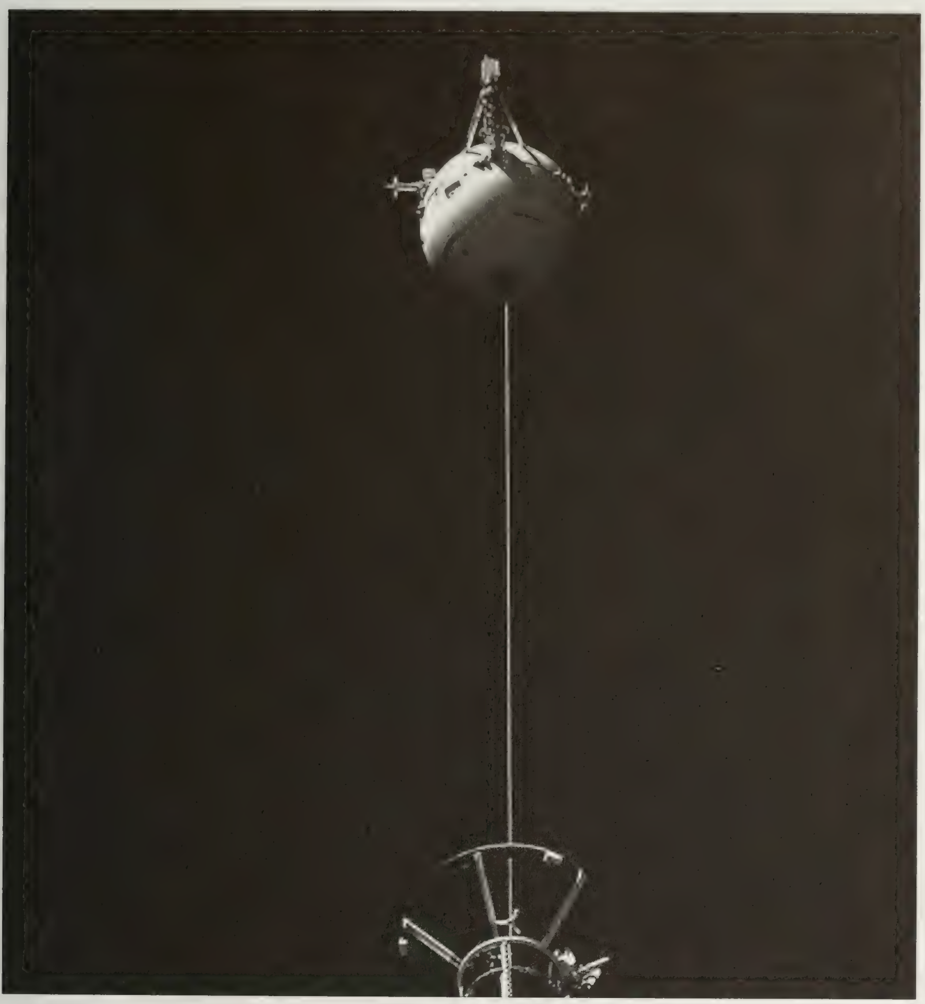

Figure 2–28. The Magellan Spacecraft with its attached Inertial Upper Stage (IUS) Booster is in the Orbiter Atlantis *Payload Bay prior to closure of the doors at T-3 days to launch. Launch of Magellan and STS-30 took place on May 4, 1989. (KSC Photo No. 89PC-0469)*

A second attempt to deploy a tethered satellite from the Shuttle was made on STS-75, launched February 22, 1996. This second attempt also failed to satisfy all the mission objectives. Although the tether unreeled smoothly for almost its full length of 13 miles (21 kilometers), the 0.1-inch (0.25-centimeter)-diameter tether broke about three-fourths of a mile before reaching full length, and the Italian satellite drifted away. There was a low-power current of 3,500 volts and 500 milliamps generated by the unreeling tether in Earth's magnetic field, which satisfied the test's scientific objective.[76]

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[76] David M. Harland, *The Story of the Space Shuttle* (Chichester, UK: Springer, Praxis Publishing, 2004), pp. 123, 137. Also Dennis R. Jenkins, *Space Shuttle: The History of the National Space Transportation System, The First 100 Missions* (Cape Canaveral, FL: Dennis R. Jenkins, 1996), p. 309.

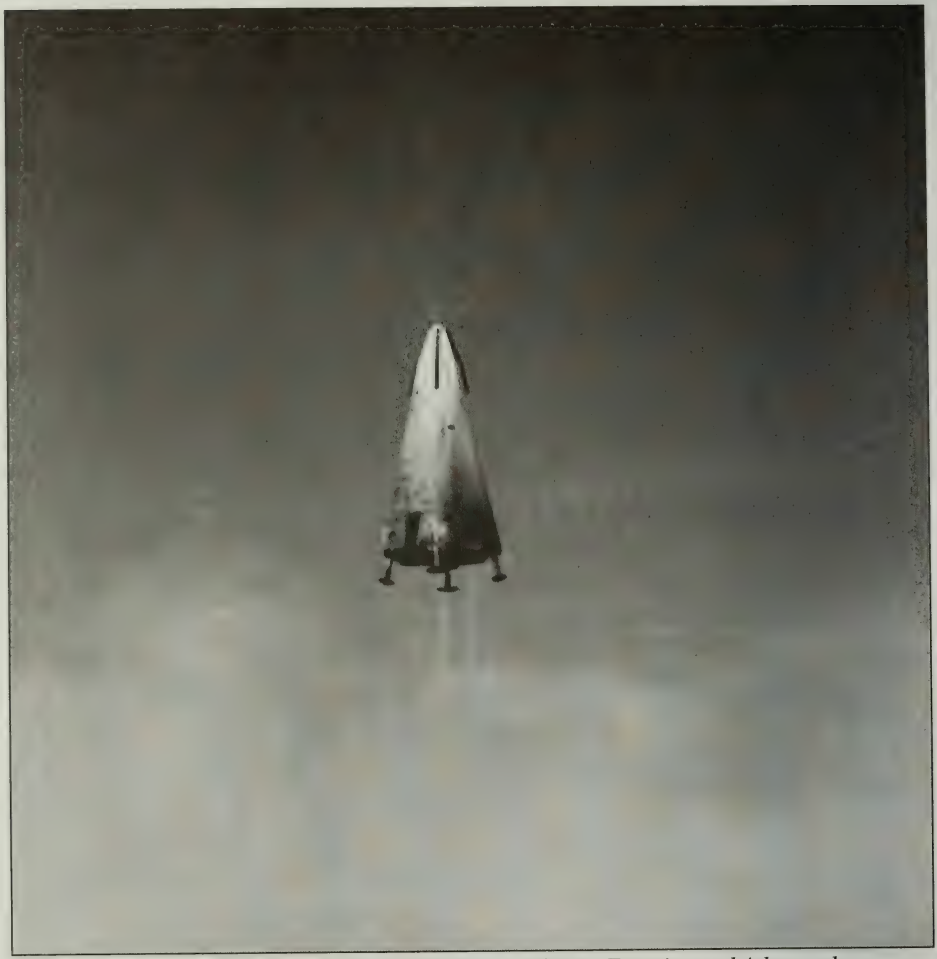

Figure 2–29. First Test Flight of the Delta Clipper-Experimental Advanced (DC-XA), May 18, 1996. (NASA-MSFC Photo No. MSFC-9607854)

A series of less complex tethered experiments took place in 1993 and 1994 from Delta II launch vehicles. They were designed to complement to the TSS deployer when retrieval of the tether was not required. The Small Expendable Deployer System (SEDS-1) was the first of three tether experiments managed by NASA's Office of Space Systems Development Flight Demonstration Program. These experiments were more successful than the Shuttle-based attempts.

On March 29, 1993, about 63 minutes after launch, the first SEDS diagnostic payload was ejected from the Delta by springs. The tether was deployed at an altitude of 720 kilometers (447 miles) above Earth and pointing toward Earth. The tether unreeled smoothly for its full 20-kilometer (12.4-mile) length, and sensors recorded its damping motion for 14 minutes. Then the tether was cut and its 30-kilogram (66-pound) cargo floated away, ending the experiment. A second successful experiment took place from a Delta on June 26, 1993. Called the Plasma

Motor Generator, this experiment assessed the ability of a space tether to generate an electric current. The tether generated about 0.3 amp of current as it moved through Earth's magnetic field.[77] A third experiment took place on March 11, 1994, when the SEDS-2 payload unreeled to its maximum length of 19.8 kilometers (12.3 miles) in 1 hour and 48 minutes. Unlike SEDS-1, when the tether was severed, the tether on this mission remained attached to the Delta rocket, and the payload at the end of the tether transmitted for 10 hours until its battery died.[78]

Shuttle-C

Shuttle-C (cargo) was a concept for a large, uncrewed launch vehicle with a cargo canister in place of the orbiter that would make maximum use of existing Space Shuttle systems. This proposed cargo-carrying launch vehicle would be able to lift approximately 100,000 pounds to 170,000 pounds (45,300 kilograms to 77,000 kilograms) to low-Earth orbit, two to three times the capability of the Shuttle's orbiter. It could reduce by 50 percent the number of launches and length of assembly time for Space Station components. It could also carry scientific spacecraft into orbit. The vehicle would use the same type of external tank, solid rocket boosters, and main engines as the crewed Space Shuttle. Although the U.S. House Subcommittee on VA-HUD-Independent Agencies authorized $1.1 billion on a heavy-lift space cargo vehicle in FY 1991, the vehicle never moved past the study stage and was replaced by the National Launch System, another short-lived initiative.

Advanced Launch System

The Advanced Launch System (ALS) was a joint NASA-DOD program of the late 1980s that was a product of the Strategic Defense Initiative (SDI) "Star Wars" ballistic missile defense system. The program was to define concepts and develop technology for a family of uncrewed launch vehicles that would reduce the cost of putting payloads into orbit. Initially, it was projected that new heavy-lift launchers would be needed to deploy payloads of 10,000 pounds to 200,000 pounds (4,500 kilograms to 90,700 kilograms) to low-Earth orbit for the space-based elements of the SDI program. Three basic booster concepts were proposed. The least costly vehicle would use a hydrogen core and from 6 to 12 solid rocket boosters. A more costly vehicle used a liquid core and from one to six strap-on liquid rocket engines. The most expensive and most advanced ALS alternative, and the least likely because of technological uncertainty, was a winged, fully reusable booster.[79] NASA managed development of the advanced liquid cryogenic propulsion system and the advanced development program.

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[77] Joel W. Powell, "Satellite Tethers Unwind," *Spaceflight*, 36 (March 1994): 97–99.

[78] "Jonathan's Space Report," no. 188 (March 14, 1994*), http://www.planet4589.org/space/jsr/back/news.188* (accessed March 21, 2005).

[79] Mark Cleary, "Future Space Operations: The Space Transportation Architecture Study and Advanced Launch System (ALS) Studies," *Military Space Operations, 1971–1992*, 45th Space Wing History Office, *https://www.patrick.af.mil/heritage/Cape/Cape4/cape4-2.htm* (accessed March 24, 2005).

However, by late 1989, the Cold War was waning, and the SDI initiative was greatly reduced in scope. In October 1989, funding cutbacks shifted emphasis to lightweight weapons, which reduced payload requirements dramatically. On December 7, 1989, the Secretary of the Air Force directed the ALS program office to terminate design efforts "as soon as possible" and suspend any new spending. The three ALS contractors, Boeing, General Dynamics, and a Martin Marietta-McDonnell Douglas team, were directed to transfer ALS technology to the existing fleet of ELVs, which all stood to benefit from technologies developed for the ALS program.[80] In January 1990, the program was downscaled to focus on propulsion technologies, particularly the Space Transportation Main Engine, although little funding was provided to pay for the project at the time.

National Launch System

One of the recommendations in the December 1990 report of the Advisory Committee on the Future of the U.S. Space Program, headed by Norman Augustine, was that the U.S. Space Program end reliance on the Shuttle. It stated that the Administration should provide funds for a "firm program for development of an evolutionary, unmanned but man-rateable, heavy-lift launch vehicle" that "should reach operational capability in time to support all but the initial phase of the Space Station deployment."[81] On January 2, 1991, Vice President Daniel Quayle directed NASA and the DOD to jointly develop a plan for a new space launch system. On April 16, 1991, the Vice President and the National Space Council directed the two organizations to "pursue the development of a new space launch system with the objective of achieving significant improvements in reliability, responsiveness, and operational efficiency."[82] This plan would meet civil and military space needs and actively consider commercial space requirements; costs would be shared equally by NASA and the Defense Department.[83]

The ensuing program, the National Launch System, sometimes called the New Launch System, replaced and combined elements of the previous Advanced Launch System and NASA's Shuttle-C programs. As stated by NASA, program goals were to: 1) develop a modular launch system with a medium-lift to heavy-lift capability, 2) facilitate evolutionary changes as requirements evolved into the 21st century, 3) use existing components from the Shuttle and ELVs to expedite initial capability and reduce development costs, and 4) develop a system that, while being uncrewed initially, could be "man-rated" in the future.[84] The proposed heavy-lift space cargo vehicle would support the logistics requirements of Space Station *Freedom*. Evolution of vehicles that could support the Nation's return to the Moon and mission to Mars was also envisioned.[85] NASA's Office of Space Systems Development managed the program.

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[80] Cleary, *Military Space Operations*," *https://www.patrick.af.mil/heritage/Cape/Cape4/cape4-2.htm*. Also, Department of Defense and National Aeronautics and Space Administration *National Space Launch Program Report to Congress*, (March 14, 1989), p. 20.

[81] Advisory Committee on the Future of the U.S. Space Program, "Report of the Advisory Committee on the Future of the U.S. Space Program," December 17, 1990, *http://www.hq.nasa.gov/office/pao/History/augustine/racfup1.htm* (accessed March 15, 2005).

[82] *Aeronautics and Space Report of the President, Fiscal Year 1992 Activities*, p. 18.

[83] David N. Spires and Rick W. Sturdevant, "Epilogue: 'To the Very Limit of Our Ability,'" in Launius and Jenkins, *To Reach the High Frontier*, p. 488.

In August 1991, NASA awarded study contracts for the NLS, each valued at $500,000, to Lockheed Missiles and Space, McDonnell Douglas, and TRW Inc. The NASA FY 1992 budget request for the NLS increased the estimate from $23.9 million for the ALS and Shuttle-C to $175 million for NASA's share of the funding. It was anticipated that activities in FY 1992 would focus on beginning development of the Space Transportation Main Engine (STME) prototype, conducting definition and design studies of vehicle components and elements, and assessing requirements and design options for supporting launch facilities.[86]

Initially, the system comprised three different-sized launch vehicles with varying payload capacities to low-Earth orbit. They would be derived from a common core element consisting of the Space Shuttle external tank and a new STME. In 1992, NASA eliminated the largest rocket from the original three when a study determined that the needed modular family of vehicles should span the medium launch vehicle class up to a booster capable of supporting the Space Station's resupply missions. One of the proposed vehicles would be able to deliver 50,000 pounds (22,680 kilograms) to low-Earth orbit; the second, smaller vehicle, could deliver 20,000 pounds (9,000 kilograms).

The program continued into 1992, although funding for FY 1993 was reduced by $137 million consistent with a first launch in 2002. The remaining $28 million was earmarked to support development of the STME. However, in early 1993, the program was terminated, and no funding was included in the FY 1994 budget.

Reusable Launch Vehicles

Developing an RLV, either to supplement or replace the Space Shuttle, received a great deal of attention and significant resources during the decade beginning in 1989. The National Aerospace Plane (the X-30), a program supported strongly by President Ronald Reagan, had been initiated in 1982 as a DARPA project. Planned as a new reusable, air-breathing, single-stage-to-orbit hypersonic vehicle, the X-30 became a joint NASA-DARPA program in 1985. Although the project produced some important technological advances, it became too costly in a time of competing priorities, and the program was cancelled in 1994 while still in the technology development phase.

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[84] "New Launch System," NASA Fact Sheet, National Aeronautics and Space Administration, Marshall Space Flight Center, August 29, 1991 (NASA History Office Folder 010274). Also, "National Launch System–NLS," FAS Space Policy Project, Military Space Programs, *http://www.fas.org/spp/military/program/launch/nls.htm* (accessed March 24, 2005).

[85] "NASA Awards Study Contracts for National Launch System," *NASA News* Release C91-gg, August 16, 1991 (NASA History Office Folder 010274).

[86] "New Launch System," *National Aeronautics and Space Administration FY 1992 Budget Estimate*, pp. RD 2-18–2-19.

NASA Administrator Goldin joined NASA in April 1992, a time when the Shuttle and other NASA programs were under attack from Congress for their high costs. Taking advantage of the change in presidential administrations in 1993, and also to put his mark on the Agency, Goldin initiated the "Access to Space" study to identify alternative, less expensive approaches to gain access to space that would also increase safety for flight crews. Released in January 1994, the study report was followed later that year by the first executive policy specifically recommending development of an RLV. On August 5, 1994, President William Clinton issued the National Space Transportation Policy making NASA "the lead agency for technology development and demonstration of next generation reusable space transportation systems," while the DOD was given responsibility for improving ELVs.[87] The policy statement led directly to the formation of NASA's RLV Technology program.

NASA's RLV Technology program was a partnership among NASA, the U.S. Air Force, and private industry to develop a new generation of single-stage-to-orbit launch vehicles. The program consisted of the Delta Clipper-Experimental Advanced (DC-XA), X-34, X-33, and related long-term technology development efforts. RLV program managers committed themselves to developing new operations and component technologies, as well as producing an industry-Government relationship that would change the space launch industry worldwide.

DC-X

The Delta Clipper-Experimental (DC-X) program, initiated by the Ballistic Missile Defense Organization (BMDO) in 1990, supported NASA's RLV program. It successfully tested an experimental suborbital launch vehicle in a series of flight tests beginning in 1993. The early RLV efforts were conducted by the U.S. Air Force Phillips Laboratory at Kirtland Air Force Base, New Mexico, under the auspices of the BMDO Single Stage Rocket Technology program. This program's charter was to demonstrate the practicality, reliability, operability, and cost efficiency of a fully reusable rapid turnaround single-stage rocket, with the ultimate goal of aircraft-like operations of RLVs. The program focused on using existing technologies and systems to demonstrate the feasibility of building RLVs for suborbital and orbital flight that could fly into space, return to the launch site, and be serviced and ready for the next mission within three days.

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[87] The White House, Office of Science and Technology Policy, Presidential Decision Directive, National Science and Technology Council-4, *National Space Transportation Policy*, August 5, 1994, *http://www.au.af.mil/au/awc/awcgate/nstc4.htm* (accessed March 20, 2005).

A design and risk reduction competition awarded McDonnell Douglas a $60 million contract in August 1991 to build the DC-X. The DC-X design emphasized simplified ground and flight operations and vehicle maintenance, rapid turnaround, and operational characteristics also relevant to future orbital vehicles. Table 2–92 lists its characteristics.

The flight test program took place in mid-1993. It started with low-altitude hover flights gradually increasing in altitude and duration and eventually leading to suborbital flights to approximately 18,000 feet (5,486 meters). The DC-X flew a total of eight test flights in 1993, 1994, and 1995; the 1995 flights supported NASA's RLV program. The test flight on June 27, 1994, experienced an on-board fire and successfully demonstrated the vehicle's autoland capabilities. On the July 7, 1995, flight, following a successful flight that demonstrated the vehicle's ability to turn itself around and reverse direction, the aeroshell cracked during landing, damaging the vehicle and ending the tests. At the conclusion of this test, the DC-X was officially turned over to NASA. The vehicle was returned to McDonnell Douglas for conversion into the DC-XA.[88]

The DC-XA was a modified DC-X with technology intended for use in the X-33 or X-34 RLVs being developed by NASA and industry partners. The DC-XA had a lightweight graphite-epoxy liquid hydrogen tank and an advanced graphite/aluminum honeycomb intertank built by McDonnell Douglas; an aluminum-lithium liquid oxygen tank built by Energia; and an improved reaction control system from Aerojet. These improvements reduced dry vehicle mass by 620 kilograms (1,367 pounds). NASA and the DOD operated the DC-XA under NASA's RLV program. The flight vehicle was tested at White Sands, New Mexico, during the summer of 1996. It demonstrated a short 26-hour turnaround time between its second and third flights, a record for any rocket.

The DC-XA flew until it was destroyed. During its fourth demonstration flight on July 31, 1996, a landing strut failed to extend, causing the unbalanced vehicle to tip over on the landing pad. The liquid oxygen tank exploded and there were indications of secondary explosions in the liquid hydrogen tank. The ensuing fire damaged large sections of the vehicle. An investigation board later determined that an unconnected helium pressurant line supplying hydraulic pressure to extend the landing strut caused the explosion. The program ended due to lack of funding to build a new vehicle. All flight tests are listed in Table 2–93.

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[88] "DC-X Fact Sheet," BMDOLINK, *http://www.hq.nasa.gov/office/pao/History/x-33/dcx-facts.htm* (accessed March 22, 2005).

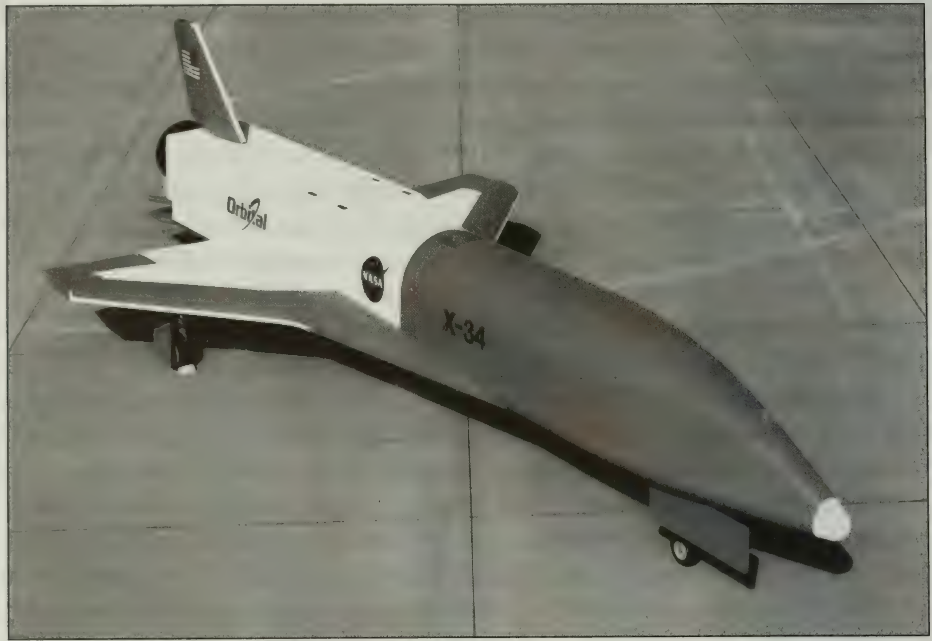

Figure 2–30. The X-34 Testbed Demonstrator being delivered to Dryden Flight Research Center, April 16, 1999. (NASA-DFRC Photo No. EC99-44976-31)

X-34

The X-34 program was to bridge the gap between the earlier subsonic DC-XA vehicle and the larger and higher performance X-33 demonstrator. It was structured originally as a cooperative agreement between NASA and Orbital Sciences Corporation signed in March 1995. The government team included Marshall Space Flight Center, responsible for the main propulsion system, including the Fastrac engine; Langley Research Center, responsible for wind tunnel testing and analysis; Ames Research Center, responsible for the thermal protection system; Dryden Flight Research Center; Holloman Air Force Base; White Sands Test Facility; and White Sands Missile Range, responsible for testing and flight support operations.

The proposed winged, reusable, single-stage vehicle, propelled by a kerosene/liquid oxygen engine, was expected to demonstrate key technologies. These included 1) composite primary and secondary airframe structures; 2) cryogenic insulation and propulsion system elements; 3) advanced thermal protection systems and materials; 4) low-cost avionics, including differential Global Positioning and inertial navigation systems; and 5) key operations technologies such as integrated vehicle health-monitoring and automated checkout systems. It was expected to significantly reduce mission costs for sending 1,000-pound to 2,000-pound (454-kilogram to 907-kilogram) payloads into low-Earth orbit. The vehicle would be air-dropped from beneath Orbital's L-1011 aircraft, reach speeds of Mach 8, and fly at altitudes of approximately 50 miles (80 kilometers). The vehicle would also demonstrate the ability to conduct subsonic flights through rain or fog and autonomous landings in crosswinds of up to 20 knots (23 miles per hour or 37 kilometers per hour). Characteristics of the technology demonstrator are listed in Table 2–94.

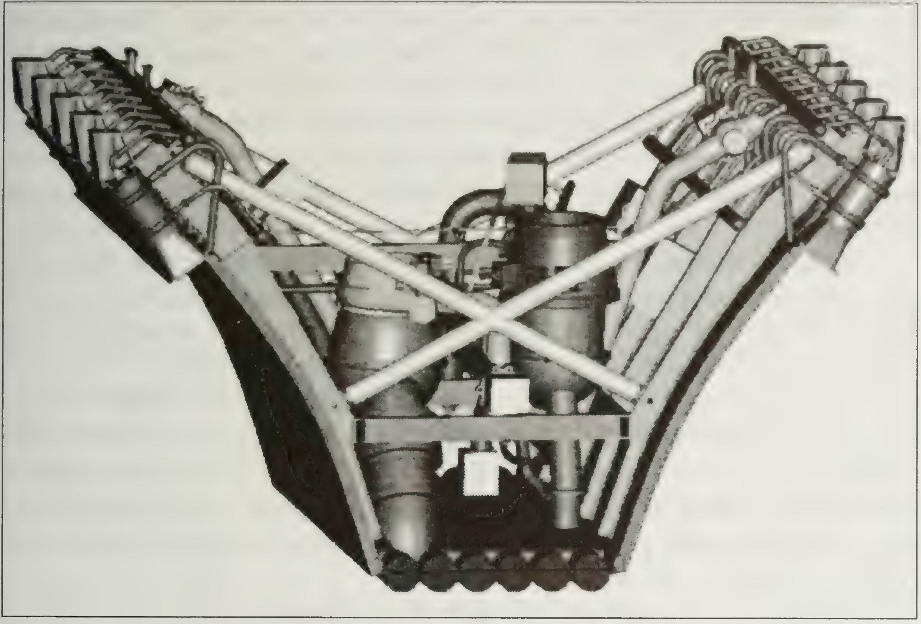

Figure 2–31. Aerospike Engine. (NASA-MSFC)

Originally, the X-34 was to progress rapidly through hardware design, flight tests planned for late 1997, and a launch expected by mid-1998. Orbital, however, withdrew from the cooperative agreement in less than a year partly because of changes in the projected profitability of the venture. NASA subsequently structured a new NASA Research Announcement in March 1996 focusing on the technology demonstration flight tests rather than on the commercial potential of the vehicle. NASA awarded the restructured fixed-price contract to Orbital in June 1996. This 30-month contract had a value of approximately $49.5 million. It included two powered test flights scheduled to begin in late 1998. NASA would spend an additional $10 million in direct support of the X-34. The contract had an option for up to 25 additional test flights after the initial contract period ended.[89]

In August 1997, a critical series of tests on the Fastrac engine were successfully completed at Marshall Space Flight Center. The Fastrac engine, only the second U.S.-made engine developed in the last 25 years, was to be the primary propulsion system for the X-34 demonstration vehicle when it began its flight tests.[90] The following May, a government-Orbital review was held finalizing the design of the vehicle. This allowed the program to proceed with fabrication and manufacturing of systems such as structures; guidance; navigation and control; avionics; thermal protection; and main propulsion systems.[91]

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[89] "NASA Finalizes X-34 Contract With Orbital Sciences Corp.," NASA Marshall Space Flight Center News Releases, Release 96-161, August 30, 1996, *http://www.msfc.nasa.gov/news/news/releases/1996/96-161.html* (accessed March 23, 2005).

To reduce program risk, NASA decided in January 1998 to modify its contract with Orbital to provide for a second flight vehicle. The modification also would allow for additional unpowered tests and more flexibility in demonstrating various technologies. The change increased the contract value by $7.7 million to purchase long lead-time hardware. NASA committed $2 million more for wind tunnel testing, additional testing and analysis, and a second leading-edge thermal protection system. An $8.5 million option called for purchase of shorter lead-time hardware, while a $1.8 million option was added for assembly.

In July 1998, the program passed a critical milestone as the first wing assembly completed qualification tests and was shipped to Orbital Sciences and mated to the X-34 test vehicle under construction. It was ultimately to fly aboard one of the two flight vehicles under construction at Orbital.

At the end of 1998, NASA exercised its option with Orbital for 25 additional test flights during a 12-month period beginning immediately after completion of the initial contract. Flights were to take place at the U.S. Army's White Sands Missile Range in New Mexico. The option was valued at more than $10 million, with government organizations performing an additional $4.7 million in work.[92]

The first of three planned X-34 technology demonstrators "rolled-out" on April 30, 1999, at Dryden Flight Research Center. The vehicle took its first test flight locked underneath the L-1011 carrier aircraft in June 1999. In August 1999, an $11 million contract for the Fastrac engine was awarded to Summa Technology. Assembly and preflight tests continued through 2000. However, in 2001, NASA decided not to add funds to the X-34 program from money dedicated to the Agency's Space Launch Initiative because the government determined that "the benefits to be derived from continuing the X-34 program did not justify the cost." This action coincided with the end of NASA's contract with Orbital Sciences Corporation. At the project's end, NASA had spent $205 million on the X-34 since its inception in 1996.

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[90] "X-34 Fastrac Engine Passes Critical Tests," *NASA News* Release 97-232, August 14, 1997, *http://www.msfc.nasa.gov/news/news/releases/1997/97-232.html* (accessed March 23, 2005).

[91] "X-34 Systems Design Freeze Completed," *NASA News* Release 97-107, May 22, 1997, *http://www.qadas.com/qadas/nasa/nasa-hm/0872.html* (accessed March 25, 2005).

[92] "NASA Exercises X-34 Contract Option for 25 Test Flights," Marshall Space Flight Center News Releases, Release 98-251, December 18, 1998, *http://www.msfc.nasa.gov/news/news/releases/1998/98-251.html* (accessed March 23, 2005).

X-33

The X-33 program, the third RLV program, was to demonstrate a half-scale, single-stage-to-orbit vehicle that could go from launch to orbit without using multiple stages like ELVs or dropping rocket motors and fuel tanks like the Space Shuttle. Flying as fast as Mach 15, it was to decrease the per-pound cost of putting payloads into space from $10,000 to $1,000, while at the same time dramatically increasing launch vehicle safety and reliability. Ultimately, the goal of the full-size vehicle, named the "VentureStar," was to resupply the Space Station more quickly and cheaply than the Space Shuttle.

The program was a high-risk venture with unproven technologies that challenged its developers. In particular, the design required development of linear aerospike rocket engines, which had never been used in flight and had been rejected by Space Shuttle developers 25 years earlier. The program required the development of a wingless "lifting body" airframe that could keep the vehicle flying smoothly during launch and return to Earth. The program also required composite fuel tanks that could withstand the pressures of a space launch while filled with pressurized liquid hydrogen at a temperature of -423°F (-253°C).[93]

NASA initiated this NASA-industry partnership through a Cooperative Agreement Notice for Phase I concept definition and design of a technology demonstrator vehicle, the X-33, issued in January 1995. In March, NASA signed cooperative agreements with three companies—Lockheed Advanced Development Company (the Skunk Works), McDonnell Douglas Aerospace, and Rockwell International Corporation—to design the vehicle. The agreement called for NASA to work with each of these companies over the next 15 months on vehicle concept definition and design. The government would provide approximately $7 million to each of the companies, and each company was expected to match the investment.

Each company produced a design concept: all the vehicles would take off vertically, but only the McDonnell Douglas concept would land vertically. The others landed horizontally like an airplane.

At the beginning of April 1996, NASA issued another Cooperative Agreement Notice for Phase II of the project: the design, fabrication, and flight test of the X-33 demonstrator. It was planned that Phase II of the project would culminate in flight demonstration testing of the X-33 to begin in early 1999. NASA and industry would share costs during this phase. This was the first time a cooperative agreement rather than a conventional contract was used for a program of this size.

After a selection process of only a few months (due to an innovative paperless procurement process), on July 2, 1996, amid much fanfare, Vice President Albert Gore announced that NASA had selected Lockheed Martin to build the X-33 test vehicle. According to the terms of the agreement, by March 1999, Lockheed Martin would design, build, and conduct the first test flight of the remotely piloted demonstration vehicle and would conduct at least 15 flights by December 1999. Major components would include a more robust metal heat shield in place of the Space Shuttle's tiles and an updated aerospike engine. The X-33 design was based on a lifting body shape that would be launched vertically like a rocket and land horizontally like an airplane. NASA had budgeted $941 million for the effort. Lockheed Martin initially invested $220 million of its own funds in the design. Figure 2–33 shows an artist's concept of the X-33 and VentureStar. Table 2–95 lists X-33 characteristics.

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[93] "NASA's Billion-Dollar Shuttle Replacement May Never Fly," *CNN.com/Space* (September 25, 2000), *http://archives.cnn.com/2000/TECH/space/09/25/troudledspaceship.ap/index.html* (accessed March 24, 2005).

In 1997, the project successfully passed two important milestones. The Critical Design Review (CDR), held in October, ended 51 subsystem and component CDRs that had been held earlier that year. It allowed the program to proceed with fabrication of the remaining components, completion of subsystems, and assembly of the subscale prototype launch vehicle. Earlier in the year, the project had needed to resolve issues regarding aerodynamic stability and control and vehicle weight by modifying the design of the vehicle's canted and vertical fins. The project also planned to reduce weight by using composite materials and densified propellants.[94] In November, NASA completed the environmental impact statement process, which allowed all 15 test flights to proceed from the launch site at Haystack Butte on the eastern part of Edwards Air Force Base, California, and land at Michael Army Air Field, Dugway Proving Ground, Utah, and Malmstrom Air Force Base near Great Falls, Montana.[95]

The next major milestone was completion of flight-testing of the thermal protection system (TPS) materials. The tests took place in June 1998 at Dryden Flight Research Center on its F-15B Aerodynamic Flight Facility aircraft. The plane reached an altitude of 36,000 feet (10,973 kilometers) and a top speed of Mach 1.4 during the tests. The materials in the TPS included metallic Inconel tiles, soft Advanced Flexible Reusable surface insulation tiles, and sealing materials.

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[94] "X-33 Program Successfully Completes Critical Design Review," *NASA News* Release 97-250, October 31, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-250.txt* (accessed March 15, 2005).

[95] "NASA Completes X-33 Environmental Impact Statement Process," *NASA News* Release 97-254, November 5, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-254.txt* (accessed March 15, 2005).

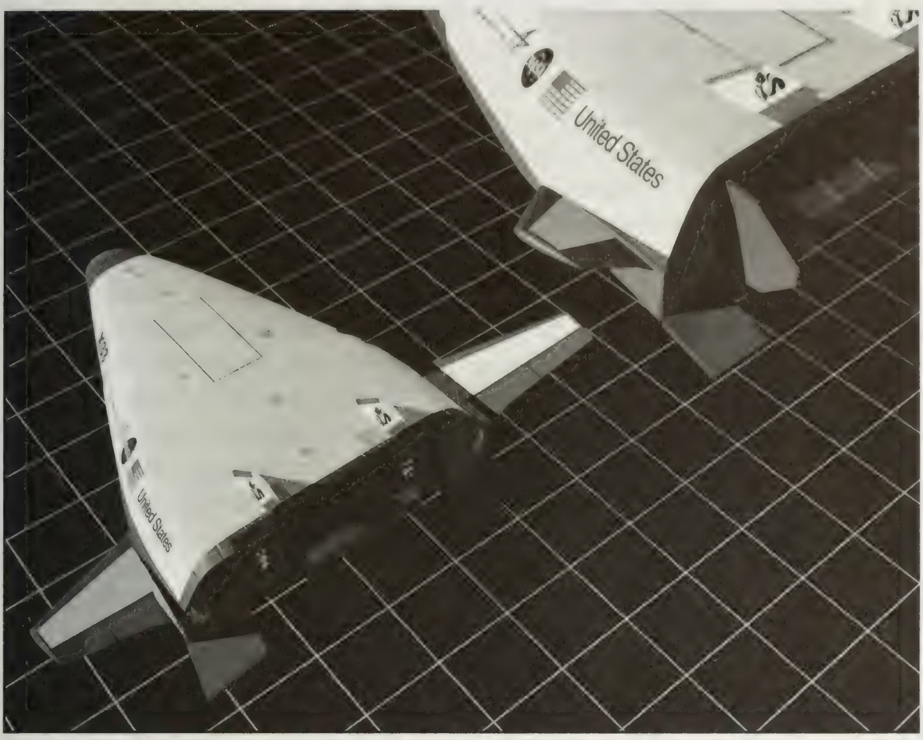

Figure 2–32. Artist's concept showing the relative size of the X-33 (left) and the proposed operational VentureStar. The VentureStar was to be twice the size of the half-scale X-33. (NASA-DFRC Photo No. ED97-43938-1)

Meanwhile, NASA's Office of Inspector General was investigating the program. The first inquiry examined whether NASA's use of a cooperative agreement on the X-33 program was appropriate for the program and "whether the agreement effectively defined roles, responsibilities, and rights of the government and industry partners." A secondary objective was to determine whether NASA implemented and managed the program consistent with congressional guidance. An audit determined that obligated funds for Lockheed Martin had not been recorded in a timely manner, a potential violation of federal law. Consequently, the Inspector General concluded that reports and financial statements "did not accurately reflect the financial status" of the program.[96] The next year, another audit from the Office of Inspector General examined whether the government had adequately addressed the cost of the project and its cost risk and cost estimate. The audit concluded that a better risk analysis "would have alerted NASA decision-makers to the probability of cost overruns" that "put NASA's investment . . . at risk."[97]

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[96] Office of Inspector General, National Aeronautics and Space Administration, "Audit Report: X-33 Funding Issues," IG-99-001, November 3, 1998, pp. 1–3, *http://www.hq.nasa.gov/office/oig/hq/ig-99-001es.htm* (accessed March 19, 2005).

[97] Office of Inspector General, National Aeronautics and Space Administration, "Audit Report: X-33 Cost Estimating Processes," IG-99-052, September 24, 1999, pp. i–ii, *http://www.hq.nasa.gov/office/oig/hq/ig-99-052es.htm* (accessed March 15, 2005).

In 1999, the X-33 program experienced a setback when the composite materials used for its liquid hydrogen fuel tank failed during testing. An investigation into the cause of the failure determined that the composite technology was not "mature enough" for such a use. Lockheed Martin proposed replacing the composite tanks with aluminum tanks, which NASA agreed to if Lockheed Martin could obtain Space Launch Initiative funding. However, it was determined that the benefit did not justify the cost, and NASA cancelled the program in 2001 before proceeding to the next phase.[98] NASA investment in the X-33 program totaled $912 million, staying within its 1996 budget projection for the program. Lockheed Martin originally committed to invest $220 million in the X-33 and, during the life of the program, increased that amount to $357 million. In response to the cancellation, Lockheed Martin chose not to continue developing the VentureStar. A criticism of both the X-34 and X-33 programs was that NASA had not developed risk management plans until well after the programs had begun. Table 2–96 lists the chronology for NASA's RLV development.

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[98] Leonard David, "NASA Shuts Down X-33, X-34 Programs," *Space.com*, *http://www.space.com/missionlaunches/missions/x33_cancel_010301.html* (accessed March 22, 2005).

Table 2–1. Authorized/Appropriated Budget (FY 1989–FY 1998) (in thousands of dollars)

	1989	1990	1991	1992	1993	1994
R&D[a]	4,191,700	5,366,050	5,600,000	6,413,800	7,089,300	7,509,300
Space Transportation Capability Development[b]	606,600	651,500	763,400	679,800[c]	733,700[d]	751,600[e]
Upper Stages	156,200	—	—	—	—	—
Orbital Maneuvering Vehicle	—	—	45,400,000	—	—	—
Shuttle-C	—	—	40,000,000[f]	—	—	—
SFC&DC[g]	4,364,200	4,614,600	6,319,132	5,157,075	5,086,000	4,878,400
Space Shuttle Production and Operational Capability	1,335,500	1,340,300	1,364,000[h]	1,328,900	1,315,800	1,069,200
Advanced Solid Rocket Motor	51,000	35,000	—	375,000	315,000	150,000[i]
Safety Enhancements	—	75,000	—	—	—	—
Space Transportation (Shuttle) Operations	2,365,400	2,544,900	2,831,400[j]	2,970,600	3,085,200	3,006,500
Expendable Launch Vehicles (Launch Services)	—	169,500	229,200[k]	291,000	207,500	300,300
	1995	**1996**	**1997[l]**	**1998[m]**		
Human Space Flight[n]	5,573,900[o]	5,456,600	5,362,900	5,506,500		
Payload and Utilization Operations[p]	346,200[q]	315,000	271,800	247,400		
Space Shuttle Safety and Performance Upgrades	3,309,000[r]	837,000	636,000	483,400		
Space Shuttle Production and Operational Capability	—	—	—	—		
Space Shuttle Operations	—	2,341,800	2,514,900	2,494,400		
Launch Services	313,700	—	—	—		
Science, Aeronautics and Technology[s]	5,901,200	5,928,900	5,762,100	5,690,000		
Advanced Concepts and Technology/Space Access and Technology	623,000[t]	639,800	711,000	696,600[u]		
Advanced Space Transportation	—	193,000	324,700	—		

Table 2–1. Authorized/Appropriated Budget (FY 1989–FY 1998) (in thousands of dollars) (Continued)

	1995	1996	1997[l]	1998[m]
X-33 Advanced Technology Demonstration Vehicle	—	—	—	333,500
Follow-on to X-33 Focused Technology Demonstration	—	—	—	150,000
Experimental Vehicle Procurement	—	—	—	150,000

[a] Total R&D amounts were stated in the appropriations bills, not in the authorization bills. R&D amounts shown did not equal the amounts shown in subcategories. Amounts for subordinate categories were from authorization bills unless otherwise noted.

[b] Amounts authorized for Space Transportation Capability Development included the Spacelab category, addressed in chapter 3, Human Spaceflight.

[c] Includes $40 million authorized for propulsion technology development and $10 million authorized for launch vehicle design studies, including single-stage-to-orbit vehicles.

[d] Specified $30 million for development of the Space Transportation Main Engine.

[e] Included $21million to develop improvements in existing ELVs (including development of a single-engine version of the Centaur upper stage rocket) and $21.4 million to support development of advanced launch technologies, including single-stage-to-orbit technologies and components.

[f] Required in FY 1991 authorizations bill. Does not appear in programmed amounts in NASA's budget.

[g] Amounts for SFC&DC were stated in appropriations bill, not in authorization bills. Amounts for subordinate categories were from authorization bills unless otherwise noted.

[h] Of such funds, $45 million for FY 1991 was to be used for the Space Shuttle main engine, solid/rocket booster/solid rocket motor, external tank, orbiter, and the Assured Shuttle Availability program.

[i] For termination of program.

[j] Of these funds, $4 million was to be made available for the provision of launch services for eligible satellites in accordance with Section 6 of the Commercial Space Launch Act Amendments of 1988, Public Law 100-657.

[k] Launch Services (ELVs) transferred to Office of Space Science and Applications under the R&D appropriation.

[l] In the FY 1997 and FY 1998 authorization, Congress included NASA's authorization in a bill titled the Omnibus Civilian Science Authorization Act. H.R. 3322 was passed by the House. It was referred to Senate committee but was not acted upon by the Senate.

[m] Authorization bill H.R. 1275 passed by House. Referred to Senate committee but was not acted upon by Senate.

[n] Beginning with the FY 1995 estimate, and computation of FY 1993 programmed amounts, many R&D and SFC&DC amounts that involved human spaceflight moved to a single, new appropriation called Human Space Flight.

[o] Appropriated amount per Conference Committee.

[p] Formerly Space Transportation Capability Development.

[q] Included $40,000,000 to develop improvements in existing ELVs (including the development of a single-engine version of the Centaur upper stage rocket) and $46,000,000 to support development of advanced launch technologies, including single-stage-to-orbit technologies and components as well as other Space Transportation Capability Development/Payload and Utilization Operations budget categories.

[r] Amount included total Space Shuttle category: Production and Operational Capability and Operations.

[s] SAT appropriation used for some launch systems items.

[t] Included $40 million for single-stage-to-orbit technology development program, $13.6 million for University Space Engineering Research Centers, and $12.5 million for Small Spacecraft Technology Initiative.

[u] Called Advanced Space Transportation Technology in H.R. 1275

Table 2–2. Programmed Budget (FY 1989–FY 1998) (in thousands of dollars)

	1989	1990	1991	1992	1993[a]	1994	1995	1996	1997	1998
R&D/SAT					Human Space Flight[b]					
Space transportation capability Development/payload and utilization operations[c]	674,000	558,142	602,467	739,711	442,300	405,600	320,100[d]	323,000	265,300	205,400
Upper stages	131,600	79,700	82,467	41,200	47,700[e]	6,900	—	—	—	—
Engineering and technical base	160,600	181,600	208,500	210,800	214,200	180,400	165,600	169,700	144,600	102,900
Payload operations & support equipment	60,700	65,461	101,200	130,100	95,200	85,100	44,000[f]	40,600	45,900	46,700
Tethered satellite system	26,400	27,300	21,900	16,400	4,000	7,400	7,400	1,800	—	—
Orbital maneuvering vehicle	73,000	75,681	—	—	—	—	—	—	—	—
Advanced programs	52,700	34,700	35,200	34,700	—	—	—	—	—	—
Advanced projects	—	—	—	—	16,100	7,200	12,200	24,200	34,700	46,700
Advanced space transportation[g]	—	—	—	—	114,600[h]	109,100[i]	162,100	234,000	—	417,100
Advanced concepts and technology	—	—	—	—	464,900	502,400	605,400	—	—	—
Advanced transportation technology[j]	81,400	—	23,900[k]	28,000	10,000[l]	20,000	—[m]	—	—	—
Reusable launch vehicle–systems engineering and analysis	—	—	—	—	—	3,500	3,800	—	—	—
Reusable launch vehicle–technology program	—	—	—	—	—	28,400	75,500	—	—	—
Reusable launch vehicle–initial flight demo program (FDP)	—	—	—	—	—	2,300	49,200	—	—	—

Table 2–2. Programmed Budget (FY 1989–FY 1998) (in thousands of dollars) (Continued)

	1989	1990	1991	1992	1993[a]	1994	1995	1996	1997	1998
X-33 advanced technology demonstrator	—	—	—	—	—	—	—	157,500	262,000	319,300
X-34 technology demonstration program	—	—	—	—	—	—	—	30,000	20,500	26,700
Transportation technology support	—	—	—	—	—	54,900	33,600	29,500[n]	34,400	62,100
SFC&DC/HSF										
Shuttle production and operational capability/safety and performance upgrades[o]	1,121,600	1,194,949	1,313,945	1,296,400	1,131,000	1,009,700	710,000	658,400	496,000	568,400
Orbiter	159,000	148,300	186,300	158,800	—	—	—	—	—	—
Orbiter improvements	—	—	—	—	235,000	204,300	194,800	271,400	159,900	232,500
Systems integration	34,500	15,000	10,700	7,200	—	—	—	—	—	—
Extended duration orbiter	20,000	23,700	25,000	10,700	—	—	—	—	—	—
Structural spares	20,300	22,900	66,000	57,600	—	—	—	—	—	—
Orbiter spares	48,000	28,200	26,800	13,800	—	—	—	—	—	—
Flight operations upgrades	—	—	—	—	121,100	109,900	54,300	73,400	66,000	40,300
Launch site equipment	104,100	105,700	101,200	93,100	80,100[p]	81,700	50,200	24,200	58,600	115,400
Mission operations and support capability[q]	153,500	177,349	136,045	148,100	—	—	—	—	—	—
Space Shuttle main engine upgrades	—	—	—	—	320,300	355,500	318,900	234,100	196,000	170,100
Solid rocket booster[r]	121,000	72,500	50,400	34,900	—	—	—	—	—	—
Solid rocket booster improvements	—	—	—	—	1,400	23,500	39,100	7,200	800	1,200
External tank	7,000	2,700	—	—	—	—	—	—	—	—

Table 2–2. Programmed Budget (FY 1989–FY 1998) (in thousands of dollars) (Continued)

	1989	1990	1991	1992	1993[a]	1994	1995	1996	1997	1998
Super lightweight tank	—	—	—	—	—	50,800	41,200	30,700	6,000	700
Construction of facilities[s]	—	—	—	—	178,100	34,300	12,300	17,400	—	8,200
Advanced solid rocket motor	51,000	160,400	309,100	315,000	195,000	149,700[t]	—	—	—	—
Assured Shuttle availability[u]	—	—	—	104,600	—	—	—	—	—	—
Space transportation operations/ Space Shuttle operations[v]	2,612,700	2,632,400	2,752,400	3,029,300	2,857,200	2,549,000	2,444,300	2,485,400	—	2,344,400
Mission support[w]	230,900	252,600	275,000	295,900	361,000[x]	316,000	287,700	358,900	46,200	814,700
Integration	285,000	303,200	317,900	315,400	200,000	199,000	169,500	142,500	—	—
Support	182,500	194,900	194,300	196,600	—	—	—	—	—	—
Orbiter	314,100	397,800	414,500	430,700	477,000	387,900	358,700	378,500	—	507,900
Space Shuttle main engine	403,200	438,200	402,400	322,100	239,900	189,200	163,300	185,000	208,300	173,400
Solid rocket booster	704,100	458,600	577,400	542,000	172,000	158,200	163,000	153,300	151,200	152,200
Redesigned solid rocket motor	—	—	—	—	409,400	396,400	370,700[y]	395,700	412,800	360,200
External tank	295,000	344,600	378,100	354,100	300,200	252,200	305,000	327,500	352,500	336,000
Launch and landing operations	534,600	541,000	595,200	642,900	697,100[z]	650,100	621,400	544,000	801,400	—[aa]
Launch operations	481,600	484,000	539,200	578,600	—	—	—	—	—	—
Payload and launch support	53,000	57,000	56,000	64,300	—	—	—	—	—	—
Expendable launch vehicles and services	66,500	139,700	229,200[ab]	155,800	180,801	84,600	255,600	245,300	240,600[ac] 84,700[ad]	212,900[ae] 27,600[af] 39,400[ag]
Small class	13,900	11,900	14,100	32,600	25,272[ah]	10,400	—	—	—	—
Medium class	45,000	75,400	97,300	58,100	61,451[ai]	43,000	—	—	—	—

Table 2–2. Programmed Budget (FY 1989–FY 1998) (in thousands of dollars) (Continued)

	1989	1990	1991	1992	1993[a]	1994	1995	1996	1997	1998
Intermediate class	6,300	49,600	108,100	45,000	41,100[aj]	43,000	—	—	—	—
Large class	1,300	2,800	9,700	20,100	5,278[ak]	—	—	—	—	—
Launch services mission support	—	—	—	—	—	37,100	—	—	—	—

[a] Beginning with the FY 1995 estimate, and computation of FY 1993 programmed amounts, all R&D and SFC&DC amounts that involved human spaceflight moved to a single, new appropriation called Human Space Flight.

[b] HSF appropriation except where noted otherwise.

[c] Budget for Space Transportation Capability Development includes Spacelab category. This is addressed with budget information in chapter 3, Human Spaceflight.

[d] Became Payload and Utilization Operations under HSF appropriations category.

[e] SAT appropriation, Office of Space Science.

[f] Renamed Payload Processing and Support.

[g] SAT appropriation within budget category Advanced Concepts and Technology. Items include Advanced Transportation Technology, Technology Assessment and Development, Advanced Technology Maturation, In-Space Transportation, and Single Engine Centaur.

[h] SAT appropriation.

[i] Part of Office of Space Access and Technology.

[j] Called Advanced Launch Systems in FY 1989 and FY 1990. Called Advanced Launch Technology in FY 1995 budget estimate. Advanced Transportation Technology includes: advanced launch system–-civil needs, advanced launched system–-propulsion, Shuttle-C studies (funding provided within Advanced Programs under Advanced Transportation line item), and heavy-lift vehicle studies.

[k] Called New Launch System beginning in FY 1993.

[l] SAT appropriation.

[m] Advanced Space Transportation Technology was also supported by $15 million in FY 1996 and $12 million in FY 1997, funded within the Engineering and Technical Base program of the Office of Space Flight.

[n] Renamed Advanced Space Transportation Program.

[o] Changed to Safety and Performance Upgrades in FY 1993.

[p] Included Launch Site Equipment upgrades (HSF appropriation) from FY 1993.

[q] Called Mission Support Capability beginning with FY 1992 estimate.

[r] Included safety upgrades and improvements to solid rocket booster and redesigned solid rocket motor.

[s] Construction of Facilities funding for Space Shuttle projects was provided to refurbish, modify, replace, and restore facilities at Office of Space Flight Centers to improve performance, address environmental concerns of the older facilities, and to ensure their readiness to support Space Shuttle Operations.

[t] Termination funding.

[u] Name changed to Safety and Obsolescence Upgrade beginning with FY 1994 budget estimate.

[v] Name changed to "Space Shuttle Operations" beginning in FY 1993.

[w] Name of category changed to "mission operations" in FY 1992. Description of function was unchanged.

[x] Called Mission and Crew Operations.

[y] Name changed to Reusable Solid Rocket Motor. Description of activity remained the same.

[z] Not broken down into smaller budget categories. Includes payload and launch support.

[aa] Combined with Mission Support.

[ab] Expendable Launch Vehicles and Services were officially transferred to the Office of Space Science and Applications (OSSA). Actual (appropriated) costs were charged to OSSA in FY 1991.

[ac] Space Science ELVs and launch support.

[ad] Earth Science ELVs and launch support.

[ae] Moved to HSF appropriation.

[af] Space Science launch support.

[ag] Earth Science launch support.

[ah] SAT appropriation.

[ai] SAT appropriation.

[aj] SAT appropriation.

[ak] SAT appropriation.

Table 2–3. Space Transportation Capability Development/Payload and Utilization Operations Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Programmed
1989	631,300/681,000	606,600	674,000
1990	639,000/562,381	651,500	558,142
1991	773,400/602,500	763,400	602,467
1992	879,800/731,456	679,800[a]	739,711
1993	863,700/649,216	733,700[b]	442,300
1994	649,200/412,600	751,600[c]	405,600
1995[d]	356,200/320,100	819,300	320,100
1996	315,600/315,000	315,000	323,000
1997	271,800/275,300	271,800	—[e]
1998	227,400/205,400	247,400	205,400

[a] Included $40,000,000 authorized for propulsion technology development and $10,000,000 authorized for launch vehicle design studies, including single-stage-to-orbit vehicles.

[b] Specified $30,000,000 for development of the Space Transportation Main Engine for use with the Advanced/New Launch System.

[c] Included $21,000,000 to develop improvements in existing ELVs (including development of a single-engine version of the Centaur upper stage rocket) and $21,400,000 to support development of advanced launch technologies, including single-stage-to-orbit technologies and components.

[d] Payload and Utilization Operations budget category (beginning FY 1995) included same subcategories as Space Transportation Capability Development (Spacelab, Tethered Satellite System, Payload Processing and Support, Advanced Projects, and Engineering and Technical Base).

[e] No programmed amount shown.

Table 2–4. Upper Stages Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	146,200/138,800	131,600
1990	88,600/84,600	79,700
1991	91,300/82,200	82,467
1992	108,500/62,256	41,200
1993[a]	56,500/47,700	47,700[b]
1994	51,100/43,600	6,900
1995	31,800/15,200	—
1996	18,300/—[c]	—

[a] Moved to Expendable Launch Vehicle category in FY 1993, which had been relocated to OSSA in FY 1993; was a SAT appropriation.

[b] SAT appropriation, Office of Space Science.

[c] Funding for mission-unique launch services was now included under the budget request for the benefiting program. Funding support for management oversight of the entire Launch Services program rested with the Launch Vehicles Office (LVO), which was now part of the newly formed Office of Space Access and Technology. The LVO aggregated NASA, NOAA, and international cooperative ELV mission requirements. The administration, procurement, and technical oversight of launch services in the small and medium performance classes were managed by Goddard Space Flight Center (Pegasus XL, Med-lite, and Delta II). Intermediate launch services (Atlas I/IIAS) were managed by Lewis Research Center. Upper stages were managed by Marshall Space Flight Center. Kennedy Space Center was delegated responsibility for technical oversight of vehicle assembly and testing at the launch site by Goddard and Lewis and was responsible for spacecraft processing at the launch site.

Table 2–5. Engineering and Technical Base Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	158,900/155,400	160,600
1990	189,800/181,600	181,600
1991	218,500/208,500	208,500
1992	235,200/215,800	210,800
1993	224,200/214,155	214,200
1994	203,400/180,400	180,400
1995	176,400/165,600	165,600
1996	171,700/171,700	169,700
1997	151,500/148,600	144,600
1998	102,900/102,900	102,900

Table 2–6. Payload Operations and Support Equipment[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	67,300/64,700	60,700
1990	81,100/66,700	65,461
1991	122,500/101,500	101,200
1992	144,500/119,100	130,100
1993	153,600/92,100	95,200
1994	95,400/92,100	85,100
1995	62,600/36,300[b]	44,000
1996	30,300/40,600	40,600
1997	42,700/41,700	45,900
1998	51,600/43,900	46,700

[a] Name of category changed to Payload Processing and Support in FY 1995.

[b] Reduction reflected closing of four of the 10 payload processing facilities before the end of the year.

Table 2–7. Advanced Programs Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	45,000/52,700	52,700
1990	48,700/33,600	34,700
1991	53,200/35,200	35,200
1992	53,800/39,300	34,700
1993	57,700/32,897	—
1994	60,700[a]/—	—

[a] Most elements moved to Advanced Space Technology.

Table 2–8. Advanced Projects Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	16,100
1994	7,200/—	7,200
1995	15,200/12,200	12,200
1996	12,200/12,200	24,200
1997	15,200/34,700	34,700
1998	58,700/46,700	46,700

[a] Budget category not established at time of budget submission.

Table 2–9. Tethered Satellite System Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	23,800/26,400	26,400
1990	19,900/24,000	27,300
1991	17,900/21,900	21.900
1992	12,600/16,400	16,400
1993	3,400/3,400	4,000
1994	—7,400[a]	7,400
1995	9,700/7,400	7,400
1996	3,800/3,800	1,800

[a] The Tether mission was flown on STS-46 in August 1992. No further Tether missions were manifested when the initial budget estimate was prepared. In 1993, it was determined that a reflight could be readily accomplished and several improvements to enhance the probability of success were recommended. The reflight was manifested for early 1996.

Table 2–10. Orbital Maneuvering Vehicle Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	96,500/73,000	73,000
1990	107,000/76,281	75,681
1991	85,400/—[a]	—

[a] A decision was made to terminate the Orbital Maneuvering Vehicle program in June 1990. Consistent with congressional direction, no FY 1991 funding was provided.

Table 2–11. Advanced Concepts and Technology/Space Access and Technology Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Authorization	Programmed
1993	—[b]	—	464,900
1994	495,300/495,300	—	562,400
1995	608,400/642,400	623,000[c]	605,400
1996	705,600/641,300	639,800	—
1997	725,000/—	711,000	—
1998	—[d]	696,600[e]	—

[a] Funding categories dealing with advanced transportation varied frequently. Included Advanced Space Transportation, Launch Vehicle Support, and other budget categories not relevant to Launch Systems.

[b] Budget category not established at time of budget submission.

[c] $40,000,000 for single-stage-to-orbit technology development program, $13,600,000 for University Space Engineering Research Centers, and $12,500,000 for Small Spacecraft Technology Initiative.

[d] Budget category not shown in budget submission or programmed amount.

[e] Called Advanced Space Transportation Technology in H.R. 1275, "Civilian Space Authorization Act, Fiscal Years 1998 and 1999."

Table 2–12. Advanced Space Transportation Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Authorization	Programmed
1993	—	—	114,600
1994	—[b]/121,900	—	109,100
1995	103,100/162,100	—	162,100
1996	193,000/188,500	193,000	234,000
1997	324,700/336,700	324,700	336,700
1998	396,600/417.100	—	417,100

[a] Categories varied depending on year and active projects. At times they included Advanced Launch Technology, Reusable Launch Vehicles, Transportation Technology Support, New Launch System, Single-Stage Centaur, and other categories.

[b] Budget category not established at time of budget submission.

Table 2–13. Advanced Transportation Technology/New Launch System Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Authorization	Programmed
1989	13,000/81,400[b]	6,500	81,400
1990	5,000/(10,500)[c]	—	—[d]
1991[e]	53,900/23,900[f]	40,000[g]	23,900[h]
1992	175,000[i]/38,000[j]	—	28,000
1993[k]	125,000[l]/10,042[m]	—	10,000[n]
1994	—	—	20,000

[a] Called Advanced Launch System in congressional documents.

[b] Renamed Advanced Launch Systems. This was a joint NASA–DOD program with the objective of defining a new heavy-lift capability based on advanced technology that would reduce the cost of placing payloads in space. NASA had responsibility for the civil requirements not addressed by the joint ALS baseline design. The original FY 1989 budget estimate of $13 million, reflected only the civil requirements. The revised estimate of $81.4 million reflected both a reduced civil requirement of $6.5 million and the propulsion element estimated at $74.9 million.

[c] Funding was deleted in FY 1990 legislation. Total funding for Advanced Launch Systems, including NASA-managed elements, was included in the DOD budget request. NASA's Advanced Launch Systems propulsion advanced development effort was provided through reimbursable funding rather than appropriation transfers.

[d] No programmed amount shown.

[e] Included Advanced Launch Systems, Shuttle-C, Heavy Lift Vehicle Studies.

[f] This revised estimate was consistent with congressional direction. It was accommodated primarily through deferral of the Assured Crew Return Vehicle Phase B study and other program realignments.

[g] Amount specified for Shuttle-C. Other uses for funds not listed.

[h] Called New Launch System beginning in FY 1993.

[i] Increase reflected plans to proceed with the initial stages of a new launch system. Program planning for FY 1992 was not completed when the estimate was prepared. It was thought that the focus of FY 1992 activities would be initiating development of the Space Transportation Main Engine prototype, conducting definition and design studies of vehicle components and elements, and assessing requirements and design options for supporting launch facilities. Technologies and operational approaches that could reduce per-flight costs and increase system robustness would also be pursued.

[j] The budget reduction supported a change to a 2002 first launch schedule. An equal amount was budgeted by DOD.

[k] Called New Launch System beginning in FY 1993.

[l] Funding level (along with an equal amount from DOD) allowed completion of the preliminary design effort for the New Launch System.

[m] The New Launch System (formerly Advanced Transportation Technology) was to be a joint program with the DOD to develop a new family of launch vehicles that would improve national launch capability with reductions in operating costs and improvements in launch system reliability, responsiveness, and mission performance. Initial efforts focused on developing the Space Transportation Main Engine (STME) since this was the common element of all configuration. The reduction in the FY 1993 budget estimate terminated the effort on the NLS while retaining options to develop the STME and/or examine alternative engine technologies.

[n] SAT appropriation.

Table 2–14. Reusable Launch Vehicle–Systems Engineering and Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]	3,500
1995	—/4,600	3,800
1996	4,700/500	—[b]

[a] Budget category not established at time of budget submission.
[b] No programmed amount shown.

Table 2–15. Reusable Launch Vehicle–Technology Program Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]	28,400
1995	—/76,900	75,500
1996	59,300/49,500	—[b]

[a] Budget category not established at time of budget submission.
[b] No programmed amount shown.

Table 2–16. Reusable Launch Vehicle–Initial Flight Demonstration Program (FDP) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]	2,300
1995	—/47,000	49,200
1996	60,000/109,000	—[b]
1997	266,100/—[c]	—

[a] Budget category not established at time of budget submission.
[b] No programmed amount shown.
[c] No revised budget submission for this category.

Table 2–17. X-33 Advanced Technology Demonstrator Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Authorization
1996	—[b]	157,500
1997	—/246,800	262,000
1998	333,500/318,300	319,300

[a] Part of Reusable Launch Vehicle Program.
[b] Budget category not established at time of budget submission.

Table 2–18. X-34 Technology Demonstration Program Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Programmed
1996	—[b]	30,000
1997	—/36,700	20,500
1998	43,100/26,700	26,700

[a] Part of Reusable Launch Vehicle Program.

[b] Budget category not established at time of budget submission.

Table 2–19. Transportation Technology Support Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]	54,900
1995	—/33,600	33,600
1996	34,000/29,500	29,500[b]
1997	16,600/53,200	34,400
1998	43,100/26,100	62,100

[a] Budget category not established at time of budget submission.

[b] Renamed Advanced Space Transportation Program.

Table 2–20. Space Shuttle Production and Operational Capability/ Safety and Performance Upgrades Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Authorization	Programmed
1989	1,400,500/1,128,200	1,335,500	1,121,600
1990	1,305,300/1,119,500	1,340,300	1,194,949
1991	1,302,000/1,327,800	1,364,000[b]	1,313,945
1992	1,288,900/1,276,400	1,328,900	1,296,400
1993	1,021,800/1,053,016	1,315,800	1,131,000
1994	1,189,600/978,700	1,069,200	1,009,700
1995	903,900/739,800	3,309,000[c]	710,000
1996	837,000/663,400	837,000	658,400
1997	636,000/636,000	636,000	496,000
1998	483,400/553,400	483,400	568,400

[a] Included orbiter improvements, propulsion upgrades (SSME upgrades, SRB improvements, super lightweight tank), flight operations and launch site equipment upgrades, advanced solid rocket motor, and construction of facility budget categories are displayed separately below.

[b] $45 million to be used only for 1) SSME, 2) SRB/SRM, 3) ET, 4), orbiter, and 5) assured Shuttle availability.

[c] Amount for total Space Shuttle budget category, including both Production and Operational Capability and Operations.

Table 2–21. Orbiter (Orbiter Operational Capability) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	181,000/155,800	159,000
1990	157,500/125,900	148,300
1991	113,400/144,900	186,300
1992	143,300/162,100	158,800
1993	196,900/179,516	—[a]

[a] No programmed amount shown.

Table 2–22. Systems Integration (Orbiter Operational Capability) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	17,000/30,500	34,500
1990	9,000/15,400	15,000
1991	11,100/11,400	10,700
1992	19,900/9,100	7,200
1993	26,900/13,400	—[a]
1994	14,400/—[b]	—

[a] No programmed amount shown.

[b] No revised budget submission in this category.

Table 2–23. Orbiter Improvements Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	235,000
1994	215,500/127,100	204,300
1995	191,800/194,800	194,800
1996	227,900/258,700	271,400
1997	169,900/169,900	159,900
1998	137,300/232,500	232,500

[a] Budget category not established at time of budget submission.

Table 2–24. Extended Duration Orbiter (Orbiter Operational Capability) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	10,000/20,000	20,000
1990	157,500[a]/125,900	23,700
1991	15,000/25,000	25,000
1992	18,500/10,500	10,700
1993	21,700/22,600	—[b]
1994	67,700[c]/—[d]	—

[a] Funding increase reflected expectations of development of a 28-day extended duration orbiter.
[b] Budget category not established at time of budget submission.
[c] Funding was to cover the payback costs to the prime contractor for use of the cryogenic pallet kit to extend on-orbit stay time capability from the baseline 7 to 10 days to 14 to 16 days. It also was to initiate the required modifications on *Endeavour* and *Atlantis*.
[d] No revised budget request submitted in this category.

Table 2–25. Structural Spares (Orbiter Operational Capability) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	57,300/20,300[a]	20,300
1990	15,200/25,200	22,900
1991	52,400/71,000	66,000
1992	78,300/50,600	57,600
1993	51,000/35,000	—[b]
1994	35,000/—[c]	—

[a] Reduction in funding reflected slower start of structural spares program than expected.
[b] Programmed amount not shown.
[c] No revised budget request submitted.

Table 2–26. Orbiter Spares (Orbiter Operational Capability) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	54,000/55,200	48,000
1990	30,300/27,100	28,200
1991	21,700/23,300	26,800
1992	13,800/13,800	13,800
1993	9,000/9,000	—[a]
1994	—[b]	—

[a] No programmed amount shown.
[b] Activity was concluded in FY 1993.

Table 2–27. Flight Operations Upgrades Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	121,000
1994	—/107,700	109,900
1995	110,900/63,900	54,300
1996	89,000/69,400	73,400
1997	69,500/89,000	66,000
1998	51,500/70,600	40,300

[a] Budget category not established at time of budget submission.

Table 2–28. Launch Site Equipment (Launch and Mission Support) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	142,000/109,400	104,100
1990	98,500/89,400	105,700
1991	114,900/110,400	101,200
1992	79,400/85,100	93,100
1993	86,000/69,000	80,100[a]
1994	81,700/68,500	81,700
1995	76,100/40,600	50,200
1996	43,800/21,100	24,200
1997	45,50026,000	58,600
1998	40,800/67,500	115,400

[a] Launch site equipment upgrades.

Table 2–29. Mission Support Capability (Launch and Mission Support) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed[a]
1989	93,500/42,100[b]	—[c]
1990	75,600/—[d]	—

[a] Combined into Mission Operations and Support Capability.

[b] Mission support decreased as program reserves were deleted to comply with the FY 1989 appropriations general reduction.

[c] No programmed amount shown.

[d] Combined with Mission Operations Capability into Mission Operations and Support Capability.

Table 2–30. Mission Operations Capability (Launch and Mission Support) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	108,200/112,700	—[a]
1990	166,900/—[b]	—

[a] Combined into Mission Operations and Support Capability.
[b] Combined with Mission Support Capability into Mission Operations and Support Capability.

Table 2–31. Mission Operations and Support Capability (Launch and Mission Support) Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Programmed
1989	—[b]	153,500
1990	242,500/169,900	177,349
1991	150,600/142,600	136,045
1992	190,700/176,600	148,100
1993	124,700/109,100	—[c]
1994	105,400/—[d]	—

[a] Combined Mission Support Capability and Mission Operations Capability.
[b] Budget category not established at time of budget submission.
[c] No programmed amount shown.
[d] No revised request submitted.

Table 2–32. Space Shuttle Main Engine Upgrades Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	320,300[b]
1994	—/287,900[c]	355,500
1995	380,500/354,200	318,900
1996	357,200/251,300	234,100
1997	309,500/324,500	196,000
1998	231,200/170,700	170,100

[a] Budget category not established at time of budget submission.
[b] Unclear where this programmed amount originated. Some activities, e.g., the alternate turbopump and the large throat main combustion chamber, were specifically named in the SFC&DC SSME budget line item. However, "other upgrades" were not specified, so it is not clear where the costs for these previously resided since the amount was larger than the entire amount budgeted for SSME under the SFC&DC appropriation.
[c] New budget category under HSF appropriation.

Table 2–33. Solid Rocket Booster (Propulsion Systems) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	105,000/123,700	121,000
1990	106,700/75,300	72,500
1991	82,900/50,400	50,400
1992	48,600/38,200	34,900[a]
1993	43,100/30,200	—[b]

[a] Included SRB safety upgrades.
[b] No programmed amount shown.

Table 2–34. Solid Rocket Booster Improvements Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	43,100/30,200	1,400
1994	52,500[a]/23,200	23,500
1995	51,600/34,400	39,100
1996	69,000/1,400	7,200
1997	2,100/800	800
1998	6,600/3,500	1,200

[a] Included improvements to redesigned solid rocket motor.

Table 2–35. External Tank (Propulsion Systems) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	7,000/7,000	7,000
1990	2,700/2,700[a]	2,700

[a] Closeout of production funding for external tank tooling and equipment to support manufacturing rate capability requirements took place in FY 1990.

Table 2–36. Super Lightweight Tank Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]/49,500	50,800
1995	80,700/39,600	41,200
1996	32,700/44,100	30,700
1997	31,200/17,500	6,000
1998	9,200/1,800	700

[a] Budget category not established at initial time of budget submission.

Table 2–37. Construction of Facilities Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	178,100
1994	—/33,500	34,300
1995	12,300/12,300	12,300
1996	17,400/17,400	17,400
1997	8,300/8,300	8,300
1998	6,800/6,800	8,200

[a] Budget category not established at time of budget submission.

Table 2–38. Advanced Solid Rocket Motor (Propulsion Systems) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Programmed
1989	88,000/51,000	51,000	51,000
1990	121,300/125,400	35,000	160,400
1991	309,100/309,100	—[a]	309,100
1992	200,000/315,000[b]	375,000	315,000
1993	—[c]/195,000	315,000	195,000
1994	280,000/179,700	150,000[d]	149,700[e]

[a] Not stated in authorization bill.

[b] Funding for the Advanced Solid Rocket Motor was increased $115 million based on congressional direction. However, the program was terminated.

[c] Due to the tight budget environment, the Advanced Solid Rocket Motor was not included in the initial FY 1993 budget request. Congress reinstated funding in the FY 1993 appropriation at a lower funding level than for the previous year.

[d] For termination of program.

[e] Reflected program termination.

Table 2–39. Assured Shuttle Availability Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1992	122,300/104,600	104,600
1993	138,900/89,500[a]	—
1994	140,200/—	—

[a] Name changed to Safety and Obsolescence Upgrades. Included items that moved to other Safety and Performance Upgrades categories in next fiscal year, e.g., alternative turbopump, large throat main combustion chamber, hardware interface module replace, cable plant upgrades, and multifunction electronic display system.

Table 2–40. Space Transportation (Space Shuttle) Operations Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Programmed
1989	2,405,400/2,390,700	2,365,400	2,612,700
1990	2,732,200/2,636,036	2,544,900	2,632,400
1991	3,118,600/3,019,200	2,831,400[a]	2,752,400
1992	3,023,600/2,943,400	2,970,600	3,029,300
1993	3,115,200/3,015,953	3,085,200	2,857,200
1994	3,006,500/2,570,600	3,006,500	2,549,000
1995	2,420,100/2,415,297	3,309,000[b]	2,444,300
1996	2,394,800/2,485,400	2.341,800	2,485,400
1997	2,514,900/1,514,900	2,514,900	2,464,900
1998	2,369,400/2,494,400	2,494,400	2,344,400

[a] In accordance with the Commercial Space Launch Act Amendments of 1988, less than or equal to $4 million was made available for the provision of launch services for eligible satellites. *Commercial Space Launch Act Amendments of 1988*, 100th Congress., 1st sess., Public Law 100-657 (November 15, 1988).

[b] Amount was for total Space Shuttle costs, including both Shuttle Operations and Production and Operational Capability.

Table 2–41. Mission Support (Flight Operations) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	215,400/230,500	230,900
1990	247,500/253,700	252,600
1991[a]	280,500/276,500	275,000
1992	318,800/260,400	295,900
1993	338,400/329,117	361,000[b]
1994	330,900/322,800	316,000
1995	298,400/253,700	287,700
1996	284,600/358,900	358,900
1997	289,700/289,700	46,200[c]
1998	289,100/94,500	814,700[d]

[a] Name of category changed to Mission Operations.

[b] Called Mission and Crew Operations.

[c] Reflected transfer of flight operations to consolidated United Space Alliance contract from Boeing and Lockheed Martin contracts.

[d] Renamed Mission and Launch Operations. Included costs for Launch and Landing Operations.

Table 2–42. Integration (Flight Operations) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	264,100/268,800	285,000
1990	300,300/314,100	303,200
1991	335,600/319,900	317,900
1992	342,300/315,400	315,400
1993	163,000/146,000	200,000
1994	151,700/211,200	199,000
1995	190,500/168,400	169,500
1996	152,200/142,500	142,500
1997	141,200/141,200	124,700
1998	126,200/107,000	—[a]

[a] Combined with Orbiter budget category.

Table 2–43. Support (Flight Operations) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	180,600/186,400	182,500
1990	224,800/191,000	194,900
1991	199,500/205,100	194,300
1992	251,400/214,500	196,600
1993	239,000/277,000	—[a]
1994	285,200—[b]	—

[a] No programmed amount shown.

[b] No revised budget request submitted.

Table 2–44. Orbiter (Flight Hardware) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	339,400/301,300	314,100
1990	351,800/370,200	397,800
1991	397,800/442,900	414,500
1992	441,700/390,400	430,700
1993	522,700/540,853	477,000
1994	508,900/364,100	387,900
1995	292,800/359,800	358,700
1996	352,700/378,500	378,500
1997	375,400/375,400	367,900
1998	376,700/356,100	507,900[a]

[a] Included both orbiter and integration budget categories.

Table 2–45. Space Shuttle Main Engine (Propulsion Systems) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	511,800/400,500	403,200
1990	496,600/438,200	438,200
1991	430,900/388,300	402,400
1992	374,100/362,200	322,100
1993	314,600/263,200	239,900
1994	245,400/191,800[a]	189,200
1995	144,400/149,200	163,300
1996	145,600/185,000	185,000
1997	172,300/182,300	208,300
1998	184,900/204,600	173,400

[a] Change to HSF appropriation from SFC&DC took place with budget estimate for FY 1995 and revised FY 1994 budget request. Old SFC&DC SSME budget category included both production of SSME and upgrades and safety. New budget category under HSF appropriation was only for shuttle operations and did not include upgrades and safety, which was budgeted separately.

Table 2–46. Solid Rocket Booster (Flight Hardware) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	382,500/516,800	704,100
1990	537,000/487,500	458,600
1991	691,300/572,900	577,400
1992	592,400/541,300	542,000
1993	556,700/559,100	172,000
1994	515,700/156,400[a]	158,200
1995	144,900/162,200	163,000
1996	164,200/153,300	153,300
1997	174,800/150,400	151,200
1998	157,700/135,500	152,200

[a] Reduction reflected creation of new budget category: Redesigned Solid Rocket Motor.

Table 2–47. Redesigned Solid Rocket Motor (Flight Hardware) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—	409,400
1994	—[a]/368,900	396,400
1995	373,100/365,997	370,000
1996	355,400/395,700	395,700
1997	402,900/427,000	412,800
1998	434,600/380,400	360,200

[a] No initial FY 1994 budget request for Redesigned Solid Rocket Motor

Table 2–48. External Tank (Flight Hardware) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	313,300/294,600	295,000
1990	347,700/347,500	344,600
1991	378,100/377,500	378,100
1992	382,900/365,400	354,100
1993	375,900/298,200	300,200
1994	340,000/305,300	252,200
1995	379,600/329,600	305,000
1996	328,000/327,500	327,500
1997	348,700/339,000	352,400
1998	359,700/341,300	336,000

Table 2–49. Launch and Landing Operations Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	514,600/506,800	534,600
1990	492,500/471,500	541,000
1991	606,600/596,200	595,200
1992	694,400/628,300	642,900
1993	639,900/690,800	697,100[a]
1994	696,400/650,100	650,100
1995	596,400/626,400	621,400
1996	612,100/544,000	544,000
1997	609,900/609,900	801,400
1998	605,300/720,200	—[b]

[a] Included launch operations and payload and launch support.

[b] Combined with Mission Support.

Table 2–50. Launch Operations (Launch and Landing Operations) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	456,600/452,800	481,600
1990	492,500/471,500	484,000
1991	546,400/537,500	539,200
1992	629,300/567,500	578,600
1993	581,100/632,000	—
1994	637,500/—[a]	—

[a] No revised estimate submitted for this budget category.

Table 2–51. Payload and Launch Support (Launch and Landing Operations) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	58,000/54,000	53,000
1990	61,100/58,700	57,000
1991	60,200/57,700	56,000
1992	64,800/60,800	64,300
1993	58,800/58,800	—
1994	58,900/—[a]	—

[a] No revised estimate submitted for this category.

Table 2–52. Expendable Launch Vehicles and Services[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Programmed
1989	195,500/85,500	—[b]	66,500
1990	169,500/141,836	169,500	139,700
1991	229,200/229,200	229,200	229,200[c]
1992	341,900/195,300	291,000	155,800
1993	217,500/180,801[d]	207,500	180,801
1994	300,300/313,500	300,300	84,600
1995	340,900/95,800	313,700	255,600
1996	74,200/254,300	—[e]	245,300
1997	253,500/240,600	—	240,600: Space Science 84,700: Earth Science
1998	236,300/215,900: Space Science 34,800: Earth Science	—	212,900[f] 27,600: Space Science 39,400: Earth Science

[a] Included funds for upcoming missions in all classes of ELVs.

[b] Not stated in authorization bill.

[c] Expendable Launch Vehicles and Services was officially transferred to the OSSA. Actual (appropriated) costs were charged to OSSA (SAT) in FY 1991.

[d] Included amounts budgeted for upper stages.

[e] Not stated in authorization bill.

[f] Moved to HSF appropriation from SAT.

Table 2–53. Small Class (Expendable Launch Vehicles and Services) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	—[a]	13,900
1990	26,300/12,100	11,900
1991	15,000/14,800	14,100
1992	33,700/33,100	32,600
1993	27,900/25,272	25,272
1994	26,200/16,800[b]	10,400
1995	31,400[c]/4,000	—
1996	10,800/—[d]	—

[a] Budget category not established at time of budget submission.

[b] SAT appropriation from revised budget estimate.

[c] SAT appropriation.

[d] Budget category no longer appeared in budget.

Table 2–54. Medium Class (Expendable Launch Vehicles and Services) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	—[a]	45,000
1990	86,200/76,036	75,400
1991	102,90098,700	97,300
1992	81,500/61,100	58,100
1993	67,300/61,451	61,451[b]
1994	77,500/93,500[c]	43,000
1995	116,200[d]/35,600	—
1996	31,000/—[e]	—

[a] Budget category not established at time of budget submission.
[b] SAT appropriation.
[c] SAT appropriation from revised budget estimate.
[d] SAT appropriation.
[e] No revised estimate submitted for this budget category.

Table 2–55. Intermediate Class (Expendable Launch Vehicles and Services) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	—[a]	6,300
1990	54,900/50,400	49,600
1991	101,100/106,000	108,100
1992	156,500/85,000[b]	45,000[c]
1993	54,800/41,000	41,100
1994	63,200/63,200[d]	43,000
1995	70,200[e]/26,000	—

[a] Budget category not established at time of budget submission.
[b] Funding was decreased partially because the launch of TDRS-7, originally scheduled to take place from an ELV, was assigned to the Shuttle.
[c] SAT appropriation.
[d] SAT appropriation from revised budget estimate.
[e] SAT appropriation.

Table 2–56. Large Class (Expendable Launch Vehicles and Services) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	—[a]	1,300
1990	2,100/3,300	2,800
1991	10,200/9,700	9,700
1992	70,200/16,100[b]	20,100
1993	11,000/5,278	5,278[c]
1994	82,300[d]/86,400[e]	—
1995	91,300[f]/—	—

[a] Budget category not established at time of budget submission.

[b] Funding reduction due to deferral of the Cassini launch to October 1997, thereby reducing the funding requirements for the Titan IV/Centaur vehicle.

[c] SAT appropriation.

[d] Increase in large-class ELV funding requests was for Titan IV vehicle needed to support the Cassini mission, scheduled for an October 1997 launch. These funds also supported the required Centaur upper stage, with both vehicle elements purchased as a package from the U.S. Air Force.

[e] SAT appropriation from revised budget estimate.

[f] SAT appropriation.

Table 2–57. Launch Services Mission Support Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]	37,100
1995	—/37,000	—[b]
1996	37,600/—	—

[a] Budget category not established at time of budget submission.

[b] No programmed amount shown.

Table 2–58. Expendable Launch Vehicle Success Rate by Year and Launch Vehicle

Year	Athena	Atlas-G Centaur/E	Atlas I/IIA/ IIAS	Conestoga	Delta	Pegasus	Scout	Taurus	Titan	Total
1989		1/1			8/8				4/4	13/13
1990		2/2	1/1		11/11	1/1	1/1		4/5	20/21
1991		2/2	1/2		5/5	1/1	1/1		2/2	12/13
1992			4/5		11/11		2/2		3/3	20/21
1993		1/1	4/5		7/7	2/2	1/1		1/2	15/18
1994		2/2	5/5		3/3	1/3[a]	1/1	1/1	5/5	18/20
1995	0/1	1/1	11/11	0/1	3/3[b]	1/2			4/4	20/23
1996			7/7		10/10	4/5			4/4	25/26
1997	1/1		8/8		10/11	5/5			5/5	29/30
1998	1/1		6/6		12/13	6/6		2/2	2/3	29/31
Totals	2/3	9/9	47/50	0/1	79/82	21/25	6/6	3/3	34/37	202/215

[a] The Pegasus launch on May 19, 1994 did not reach its intended orbit and was classified in most sources as a "partial failure." It is counted as a failure in this table.

[b] The Delta launch on August 5, 1995 placed the Koreasat spacecraft in a lower than expected orbit. It still allowed the mission to achieve most of its objectives, although it shortened the satellite's useful life. It is counted as a success in this table.

Table 2–59. Athena Launches (1989–1998)

Launch Date	Mission	Vehicle Type	Comment
August 15, 1995	Gemstar 1	Athena I	Failed
August 23, 1997	Lewis	Athena I	Launch successful but spacecraft failed
January 7, 1998	Lunar Prospector	Athena II	Successful lunar mission

Table 2–60. Athena I Characteristics[a]

	Stage 1	Stage 2	Orbit Assist Module	Payload Fairing Envelope	Total
Length	10.7 m (35.2 ft)	3.0 m (10.0 ft)	1.0 m (3.3 ft)	6.1 m (20 ft)	18.9 m (61.9 ft)
Diameter	2.3 m (7.7 ft)	2.3 m (7.7 ft)	2.3 m (7.7 ft)	7.7 ft (2.3 m) outer; 6.75 ft (2.1 m) inner	
Inert mass	4,375 kg (9,650 lb)	1,030 kg (2,280 lb)	360 kg (790 lb)		
Gross mass	53,100 kg (117,100 lb)	10,810 kg (23,840 lb)	596 kg or 715 kg (1,310 lb or 1,570 lb)	535 kg (1,180 lb)	66,300 kg (146,100 lb)
Propulsion	Castor 120 Motor	Orbus 21D motor	Four Primex MR-107		
Propellant	HTPB	HTPB	Hydrazine		
Propellant mass	48,700 kg (107,400 lb)	8,780 kg (21,560 lb)	236 kg or 354 kg (520 lb or 780 lb)		
Avg. thrust	Sea level: 1,450 kN (325,900 lb) Vac.: (1,604 kN (360,500 lb)	187 kN (42,400 lb)	Initially 890 N (200 lb), decreases with time		1,450 kN (325,900 lb) at liftoff
Nominal burn time	83.4 sec	150 sec	1,500 sec (depends on mission)		
Max. payload	545 kg–820 kg (1,200 lb–1,805 lb) to low-Earth orbit depending on launch inclination				
Contractor	Thiokol	Pratt & Whitney	Primex Technologies	Lockheed Martin	Lockheed Martin

[a] Steven Isakowitz, Joseph P. Hopkins, Jr., and Joshua B. Hopkins, *International Reference Guide to Space Launch Systems,* 3rd ed., (Reston, Virginia: American Institute of Aeronautics and Astronautics, 1999), pp. 40–47.

Table 2–61. Athena II Characteristics[a]

	Stage 1	Stage 2	Stage 3	Orbit Assist Module	Payload Fairing Envelope	Total
Length	10.7 m (35.2 ft)	10.7 m (35.2 ft)	3.0 m (10.0 ft)	1.0 m (3.3 ft)	6.1 m (20 ft)	28.2 m (93.2 ft)
Diameter	2.3 m (7.7 ft)	2.3 m (7.7 ft)	2.3 m (7.7 ft)	2.3 m (7.7 ft)	7.7 ft (2.3 m) outer; 6.75 ft (2.1 m) inner	
Inert mass	4,375 kg (9,650 lb)	4,375 kg (9,650 lb)	1,030 kg (2,280 lb)	360 kg (790 lb)		
Gross mass	53,100 kg (117,100 lb)	53,100 kg (117,100 lb)	10,810 kg (23,840 lb)	596 kg or 715 kg (1,310 lb or 1,570 lb)	535 kg (1,180 lb)	120,700 kg (266,100 lb)
Propulsion	Castor 120 Motor	Castor 120 Motor	Orbus 21D motor	Four Primex MR-107		
Propellant	HTPB	HTPB	HTPB	Hydrazine		
Propellant mass	48,700 kg (107,400 lb)	48,700 kg (107,400 lb)	8,780 kg (21,560 lb)	236 kg or 354 kg (520 lb or 780 lb)		
Avg. thrust	Sea level: 1,450 kN (325,900 lb) Vac.: (1,604 kN (360,500 lb)	Sea level: 1,450 kN (325,900 lb) Vac.: (1,604 kN (360,500 lb)	187 kN (42,400 lb)	Initially 890 N (200 lb), decreases with time		1,450 kN (325,900 lb) at liftoff
Nominal burn time	83.4 sec	83.4 sec	150 sec	1,500 sec (depends on mission)		
Max. payload	1,575 kg to 2,065 kg (3,470 lb to 4,520 lb) to low-Earth orbit depending on orbital inclination					
Contractor	Thiokol	Thiokol	Pratt & Whitney	Primex Technologies	Lockheed Martin	Lockheed Martin

[a] Isakowitz, et al., *International Reference Guide to Space Launch Systems,* 3rd ed., pp. 40–47.

Table 2–62. Atlas Launches (1989–1998)

Vehicle Number[a]	Mission	Launch Date (Based on GMT)	Vehicle Type[b]	Comments
AC-68	Fltsatcom F-8	September 25, 1989	Atlas G Centaur	Launched by NASA/industry team for Navy. Last in NASA inventory of Atlas G Centaur rockets.
S/N 28	USA 56, 57, 58	April 11, 1990	Atlas E	DOD meteorological satellite. Classified mission.
AC-69	Combined Release and Radiation Effects Satellite (CRRES)	July 25, 1990	Atlas I	NASA–DOD mission. First Atlas I launch.
S/N 61	USA 68 (DMSP-10)	December 1, 1990	Atlas E	Defense Meteorological Satellite Program (DMSP) satellite.
AC-70	Yuri 3H (BS 3H)	April 18, 1991	Atlas I	Failed when one of the two Centaur engines did not start.
S/N 50	NOAA-12	May 14, 1991	Atlas E	NOAA weather satellite.
S/N 53	USA 73 (DMSP-11)	November 28, 1991	Atlas E	DOD weather satellite.
AC-102	Eutelsat II F3	December 7, 1991	Atlas II	European communications satellite.
AC-101	USA 78 (DSCS III-06)	February 11, 1992	Atlas II	Defense Satellite Communications Systems (DSCS) III satellite.
AC-72	Galaxy 5	March 14, 1992	Atlas I	Commercial communications satellite.

Table 2–62. *Atlas Launches (1989–1998) (Continued)*

Vehicle Number[a]	**Mission**	**Launch Date (Based on GMT)**	**Vehicle Type**[b]	**Comments**
AC-105	Intelsat-K	June 10, 1992	Atlas IIA	International communications satellite. First Atlas IIA launch.
AC-103	USA 82	July 2, 1992	Atlas II	DSCS III satellite.
AC-71	Galaxy 1R	August 22, 1992	Atlas I	Failed when one of the two Centaur engines did not start.
AC-74	UFO 1 (UHF-1)	March 25, 1993	Atlas I	Military communications satellite. Failed to reach operational orbit.
AC-104	USA 93 (DSCS III F8)	July 19, 1993	Atlas II	DSCS III satellite.
S/N 34	NOAA-13	August 9, 1993	Atlas E	NOAA weather satellite.
AC-75	UHF-2	September 3, 1993	Atlas I	U.S. Navy communications satellite.
AC-106	DSCS III	November 28, 1993	Atlas II	Military communications satellite.
AC-108	Telstar 401	December 16, 1993	Atlas IIAS	Communications satellite. First Atlas IIAS launch.
AC-73	GOES-8	April 13, 1994	Atlas I	NOAA weather satellite.
AC-76	UFO 3 (UHF-3)	June 24, 1994	Atlas I	U.S. Navy communications satellite.
AC-107	DBS-2	August 3, 1994	Atlas IIA	Communications satellite.
S/N 20	DMSP F-12	August 29, 1994	Atlas E	DMSP satellite.
AC-111	Intelsat 703	October 6, 1994	Atlas IIAS	International communications satellite.

Table 2–62. Atlas Launches (1989–1998) (Continued)

Vehicle Number[a]	Mission	Launch Date (Based on GMT)	Vehicle Type[b]	Comments
AC-110	Orion 1	November 29, 1994	Atlas IIA	German communications satellite.
S/N 11	NOAA-14	December 30, 1994	Atlas E	NOAA weather satellite.
AC-113	Intelsat 704	January 10, 1995	Atlas IIAS	International communications satellite.
AC-112	UFO-4 (USA 108)	January 29, 1995	Atlas II	U.S. Navy communications satellite.
AC-115	Intelsat 705	March 22, 1995	Atlas IIAS	International communications satellite.
S/N 45	USA 109 (DMSP-F13)	March 24, 1995	Atlas E	DMSP/F13 satellite. Last Atlas E launch.
AC-114	AMSC-1 (MSAT)	April 7, 1995	Atlas IIA	Provide mobile telephone communication.
AC-77	GOES-9	May 23, 1995	Atlas I	NOAA geostationary weather satellite.
AC-116	UHF 6 (USA 111)	May 31, 1995	Atlas II	Navy communications satellite.
AC-118	USA 113 (DSCSIII B5)	July 31, 1995	Atlas IIA	DSCS III satellite.
AC-117	JCSat 3	August 29, 1995	Atlas IIAS	Japanese communications satellite.
AC-119	UFO-6 (USA 114)	October 22, 1995	Atlas II	Military communications satellite.

Table 2–62. *Atlas Launches (1989–1998) (Continued)*

Vehicle Number[a]	Mission	Launch Date (Based on GMT)	Vehicle Type[b]	Comments
AC-121	Solar and Heliospheric Observatory	December 2, 1995	Atlas IIAS	NASA-European Space Agency space science mission.
AC-120	Galaxy 3-R	December 15, 1995	Atlas IIA	Commercial communications satellite.
AC-126	Palapa C-1	February 1, 1996	Atlas IIAS	Indonesian communications satellite.
AC-122	Inmarsat 3 F1	April 3, 1996	Atlas IIA	International communications satellite.
AC-78	Beppo-SAX	April 30, 1996	Atlas I	Italian Dutch telescope.
AC-125	UFO 7 (USA 127)	July 25, 1996	Atlas II	Military communications satellite.
AC-123	GE-1	September 8, 1996	Atlas IIA	Commercial communications satellite.
AC-124	Hot Bird 2	November 21, 1996	Atlas IIA	European communications satellite.
AC-129	Inmarsat 3 F3	December 18, 1996	Atlas IIA	Communications satellite.
AC-127	JCSat 4	February 17, 1997	Atlas IIAS	Japanese communications satellite.
AC-128	Tempo 2	March 8, 1997	Atlas IIA	Commercial communications satellite.
AC-79	GOES-10	April 25, 1997	Atlas I	NOAA geostationary weather satellite. Last Atlas I launch.
AC-133	Superbird C	July 28, 1997	Atlas IIAS	Japanese communications satellite.

Table 2–62. Atlas Launches (1989–1998) (Continued)

Vehicle Number[a]	Mission	Launch Date (Based on GMT)	Vehicle Type[b]	Comments
AC-146	GE-3	September 4, 1997	Atlas IIAS	Communications satellite.
AC-135	EchoStar 3	October 5, 1997	Atlas IIAS	Communications satellite.
AC-131	USA 133 (Lacrosse 3)/USA 135 (Defense Satellite Communications System 3 and Falcon Gold)	October 25, 1997	Atlas IIA	Military satellite.
AC-149	Galaxy 8i	December 8, 1997	Atlas IIAS	Communications satellite.
AC-109	USA 137 (Capricorn)	January 29, 1998	Atlas IIA	Military satellite.
AC-151	Intelsat 806	February 28, 1998	Atlas IIAS	International communications satellite.
AC-132	USA 138, UHF F8	March 16, 1998	Atlas II	Military communications satellite. Last Atlas II launch.
AC-153	Intelsat 805	June 18, 1998	Atlas IIAS	International communications satellite.
AC-134	Hotbird 5	October 9, 1998	Atlas IIA	Communications satellite.
AC-130	UHF F9	October 20, 1998	Atlas IIA	Military communications satellite.

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[a] Atlas Centaur vehicle numbers from Jean-Jacques Serra and Gunter Krebs, "Atlas Centaur, Atlas Centaur Launches," *The Satellite Encyclopedia, http://www.tbs-satellite.com/tse/online/lanc_atlas_centaur.html* (accessed January 24, 2005).

[b] "Atlas Launches," International Launch Services Launch Archives, *http://www.ilslaunch.com/launches* (accessed January 25, 2005).

Table 2–63. Atlas E Characteristics[a]

	1-1/2 Stages (Booster and Sustainer)	Star Apogee Kick Motor (AKM)	Fairing	Total
Length	21.3 m (69.8 ft)	0.94 m (3.1 ft)	6.9 m (22.5 ft)	Up to 28.1 m (92.1 ft)
Diameter	3.05 m (10 ft)	0.94 m (3.1 ft)	2.1 m (7 ft)	
Gross mass	121,000 kg (266,759 lb)	47.7 kg (105 lb) (weight of motor)	735 kg (1,620 lb) assembly case after depletion of fuel	121,000 kg (266,759 lb)
Propulsion	MA-3 system consisting of two LR 89-NA-5 boosters, one LR 105-NA-5 sustainer, and two LR 101-NA-7 vernier engines (VE)	TE-M-364-15 motor		
Propellant	LOX-RP-1-1	Solid		
Propellant mass	112,900 kg (248,902 lb)	666 kg (1,468 lb)		
Liftoff thrust	Booster: 1,470 kN (330,000 lb) Sustainer: 267 kN (60,000 lb) Each vernier engine: 3.0 kN (670 lb)	42.4 kN (9,532 lb)[b]		1,743 kN (391,842 lb)
Burn time (average)	Booster: 120 sec, Sustainer: 309 sec	45 sec		
Max. payload	2,090 kg (4,608 lb) to 195-km (105-nmi) orbit from polar launch with dual TE-364-4 engines; 1,500 kg (3,307 lb) to 195-km orbit from polar launch with single TE 374-4 engine			
Contractors	Rocketdyne	Thiokol		General Dynamics
Remarks	Atlas E in this decade was used primarily to launch meteorological satellites into polar or geosynchronous orbit			

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[a] Steven J. Isakowitz and Jeff Samella, *International Reference Guide to Space Launch Systems*, 2nd ed., (Washington, DC: American Institute of Aeronautics and Astronautics, 1991), pp. 206–211.

[b] "NOAA-D," Friends and Partners in Space, (downloaded to Friends and Partners from NASA Spacelink), *http://www.friends-partners.org/oldfriends/jgreen/noaa.html* (accessed January 25, 2005).

Table 2–64. Atlas G Centaur Characteristics[a]

	Atlas G Booster and Sustainer	Centaur Stage	Total
Length	22.2 m (72.8 ft)	9.15 m (30 ft)	38.0 m (125 ft) (includes fairing)
Diameter	3.05 m (10 ft)	3.05 m (10 ft)	3.05 m (10 ft)
Gross mass	145,700 kg (321,200 lb)	15,600 kg (34,300 lb)	166,140 kg (366,276 lb)[b] at liftoff (includes fairing)
Propulsion	MA-5 system consisting of two LR-89-NA-7 boosters, one LR-105-NA-7 sustainer, and two vernier engines	Two RL10A-3-3A[c] multiple-start engines and 12 small hydrogen peroxide thrusters	
Propellant	Oxidizer: LOX Fuel: RP-1	Oxidizer: LOX Fuel: LH_2	
Propellant mass	138,300 kg (305,000 lb)	13,900 kg (30,600 lb)	
Liftoff thrust	Booster: 1,680 kN (377,500 lb) Sustainer: 269 kN (60,600 lb) Each vernier engine: 3 kN (670 lb)	146.8 kN (33,000 lb) vacuum	1,950 kN (438,877 lb)
Nominal burn time	Booster: 174 sec, Sustainer: 266 sec	402 sec	
Max. payload	6,100 kg (13,448 lb) to 185 km (100 nmi) orbit; 2,360 kg (5,203 lb) to geosynchronous transfer trajectory[d]		
Contractors	Rocketdyne	Pratt & Whitney	General Dynamics
Remarks	The lower booster and sustainer stage was integrated electronically with the Centaur upper stage		

[a] Isakowitz and Samella, *International Reference Guide to Space Launch Systems*, 2nd ed., pp. 206–210. The Atlas G was almost identical to the Atlas I. Isakowitz does not list Atlas G specifications, and Atlas I specifications are used in this table unless a different reference specific to Atlas G is noted.

[b] Federal Aviation Administration, "The Evolution of Commercial Launch Vehicles," *Fourth Quarter 2001 Launch Report*, *http://ast.faa.gov/files/pdf/q42001.pdf* (accessed January 25, 2005). Also "Atlas G," *Encyclopedia Astronautica*, *http://www.astronautix.com/lvs/atlasg.htm* (accessed January 25, 2005).

[c] According to Pratt & Whitney records, the RL10-3-3A engine was used on the launch of Fltsatcom F-8 on September 25, 1989. A number of earlier Atlas G launches used the RL10-3-3 engine.

[d] *Aeronautics and Space Report of the President, 1988 Activities*, (Washington, DC: National Aeronautics and Space Administration, 1990), p. 184.

Table 2–65. Atlas I Characteristics[a]

	Atlas I First Stage	Centaur Stage	Total
Length	22.2 m (72.8 ft)	9.15 m (30 ft)	Up to 43.9 m (144 ft) with large fairing
Diameter	3.05 m (10 ft)	3.05 m (10 ft)	
Gross mass	145,700 kg (321,200 lb)	15,600 kg (34,000 lb)	164,300 kg (362,200 lb)
Propulsion	MA-5 propulsion system consisting of two LR-89-NA-7 boosters, one LR-105-NA-7 sustainer, and two vernier single-start engines	Two RL10A-3-3A multiple start engines and 12 small hydrogen peroxide thrusters	
Propellant	Oxidizer: LOX Fuel: RP-1	Oxidizer: LOX Fuel: LH_2	
Propellant mass	138,300 kg (305,000 lb)	13,900 kg (30,600 lb)	
Liftoff thrust	Booster: 1,680 kN (377,500 lb) Sustainer: 269 kN (60,600 lb) Each vernier engine: 3 kN (670 lb)	146.8 kN (33,000 lb) vacuum	1,950 kN (438,877 lb)[b]
Nominal burn time	Booster: 174 sec, Sustainer: 266 sec	402 sec	
Max. payload	6,580 kg (14,500 lb) to low-Earth orbit; 2,610 kg (5,754 lb) to geosynchronous transfer orbit; 4,300 kg (9,480 lb) to sun synchronous orbit[c]		
Contractors	Rocketdyne	Pratt & Whitney	General Dynamics
Remarks	An aluminum interstage adapter with a length of 3.96 m (13 ft), diameter of 3.05 m (10 ft), and mass of 477 kg (1,052 lb) supported the Centaur until separation took place.		

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[a] Isakowitz and Samella, *International Reference Guide to Space Launch Systems*, 2nd ed., pp. 206–210.

[b] Liftoff thrust refers only to thrust produced by the Atlas stage. Thrust produced by the Centaur upper stage is produced approximately 4 minutes, 40 seconds after liftoff.

[c] *Aeronautics and Space Report of the President, Fiscal Year 1992 Activities* (Washington, DC: National Aeronautics and Space Administration, 1993), p. 94.

Table 2–66. Typical Atlas Launch Events Sequence for a Geosynchronous Mission[a]

Event	Time After Liftoff	Altitude Miles (Km)	Downrange Miles (Km)	Speed (mph/km per hr)
Liftoff	T-0			
Atlas booster engine cutoff	2 min 35 sec	37 (60)	54 (87)	6,527 (10,504)
Jettison Atlas booster engine	2 min 38 sec	38 (61)	59 (95)	6,590 (10,606)
Jettison Centaur insulation panel	3 min 0 sec	50 (80)	70 (113)	6,967 (11,212)
Jettison nose fairing	3 min 36 sec	67 (108)	154 (248)	7,746 (12,466)
Atlas sustainer/ vernier engines cutoff	4 min 27 sec	85 (137)	258 (415)	9,326 (15,009)
Atlas/Centaur separation	4 min 29 sec	86 (138)	266 (428)	9,330 (15,015)
First Centaur main engine start	4 min 40 sec	89 (143)	286 (460)	9,306 (14,977)
Centaur main engine cutoff	9 min 53 sec	94 (151)	1,298 (2,088)	17,953 (28,893)
Second Centaur main engine start	24 min 53 sec	212 (341)	5,366 (8,636)	17,487 (28,143)
Second Centaur main engine cutoff	26 min 29 sec	241 (388)	5,836 (9,392)	22,535 (36,267)
Centaur/payload separation	28 min 44 sec	334 (538)	6,566 (10,567)	22,262 (35,827)

[a] "CRRES Press Kit," Press Kit, July 1990, (from NASA Spacelink), *http://www.flyaria.com/document/html/mission/crres/cr.htm* (accessed July 18, 2006).

Table 2–67. Atlas II Characteristics[a]

	Atlas II Stage	Centaur II Upper Stage	Total
Length	24.9 m (81.7 ft)	9.15 m (30 ft)	47.5 m (156 ft) with large fairing
Diameter	3.05 m (10 ft)	3.05 m (10 ft)	
Gross mass	165,700 kg (365,300 lb)	15,600 kg (34,300 lb)	187,600 kg (413,500 lb)
Propulsion	MA-5A system with one two-chamber RS-27 booster engine and one RS-56SA sustainer engine	Two 10A-3-3A cryogenic multiple start engines	
Propellant	Oxidizer: LOX Fuel: RP-1	Oxidizer: LOX Fuel: LH_2	
Propellant mass	155,900 kg (345,500 lb)	13,900 kg (30,000 lb)	
Avg. thrust	Booster: 1,840 kN (414,000 lb) Sustainer: 269 kN (60,500 lb)	146.8 kN (33,000 lb) (vacuum)	2,110 kN (474,500 lb)
Nominal burn time	Booster: 172 sec, Sustainer: 283 sec	402 sec	
Max. payload	6,580 kg (14,500 lb) to low-Earth orbit from Cape Canaveral; 5,510 kg (12,150 lb) to low-Earth orbit from Vandenberg AFB; 2,810 kg (6,200 lb) to geosynchronous transfer orbit		
Contractors	Rocketdyne	Pratt & Whitney	General Dynamics/ Lockheed
Remarks	The Atlas was integrated with the Centaur vehicle by an interstage adapter weighing 482 kg (1,067 lb) and measuring 3.05 m (10 ft) in diameter and 4 m (13 ft) long		

[a] Isakowitz and Samella, *International Reference Guide to Space Launch Systems,* 2nd ed., pp. 206–210.

Table 2–68. Atlas IIA Characteristics[a]

	Atlas IIA Stage	Centaur IIA Upper Stage	Payload Fairing	Total
Length	24.9 m (81.7 ft) + 4-m (13-ft) interstage	10 m (33 ft)	Large: 12.0 m (39.4 ft); extended: 12.9 m (42.4 ft)	47.4 m with large payload fairing and interstage
Diameter	3.05 m (10 ft)	3.05 m (10 ft)	4.2 m (13.7 ft)	
Inert mass	9,800 kg (21,605 lb) + 545-kg (1,202-lb) interstage	2,200 kg (4,850 lb)		
Gross mass	166,700 kg (367,510 lb) (includes interstage)	18,980 kg (41,844 lb)	Large: 2,085 kg (4,600 lb); extended: 2,255 kg (4,970 lb)	187,500 kg (413,366 lb) with large payload fairing
Propulsion	MA-5A system with one two-chamber RS-27 booster engine and one RS-56SA sustainer engine	Two RL10A-4 cryogenic multiple start engines		
Propellant	Oxidizer: LOX Fuel: RP-1	Oxidizer: LOX Fuel: LH_2		
Propellant mass	156,400 kg (344,800 lb)	16,780 kg (37,000 lb)		
Avg. thrust	Booster: 1,854 kN (416,000 lb) sea level Sustainer: 266 kN (59,800 lb) sea level	185.2 kN (41,635 lb)		2,140 kN (481,200 lb) at liftoff
Nominal burn time	Booster: 165 sec, Sustainer: 274 sec	370 sec		
Max. payload	6,192 kg (13,651 lb)–7,316 kg (16,129 lb) to low-Earth orbit with large fairing depending on launch inclination; 3,066 kg (6,760 lb) to geosynchronous transfer orbit with large fairing			
Contractors	Rocketdyne	Pratt & Whitney		Lockheed Martin
Remarks	The operational Atlas IIA had uprated RL10 engines with optional nozzle extensions for the Centaur stage.			

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[a] Isakowitz, et al., *International Reference Guide to Space Launch Systems,* 3rd ed., pp. 54, 68–73. Also, International Launch Services, *Atlas Launch System Mission Planner's Guide, Rev. 7* (December 1998), pp. 1–6, A9, *http://www.ilslaunch.com/missionplanner/pdf/ampg_r7.pdf* (accessed January 27, 2005).

Table 2–69. Atlas IIAS Characteristics[a]

	Atlas IIAS Stage	Centaur IIAS Upper Stage	Payload Fairing	Total
Length	24.9 m (81.7 ft) + 4-m (13-ft) interstage SRB: 13.6 m (44.6 ft)	10 m (33 ft)	Large: 12.0 m (39.4 ft) Extended: 12.9 m (42.4 ft)	47.4 m with large payload fairing
Diameter	3.05 m (10 ft) SRBs: 102-cm (40 in)	3.05 m (10 ft)	4.2 m (13.7 ft)	
Inert mass	9,800 kg (21,605 lb) + 545-kg (1,202-lb) interstage	2,200 kg (4,850 lb)		
Gross mass	166,700 kg (367,510 lb) (includes interstage) SRBs: 11,567 kg (25,500 lb) (each fueled)	18,980 kg (41,850 lb)	Large: 2,085 kg (4,600 lb) Extended: 2,255 kg (4,970 lb)	237,200 kg (522,900 lb)
Propulsion	MA-5A system with one two-chamber RS-27 booster engine, and one RS-56SA sustainer engine augmented with four Castor IVA SRBs	Two 10A-4 cryogenic multiple-start engines		
Propellant	Oxidizer: LOX, Fuel: RP-1	Oxidizer: LOX, Fuel: LH_2		
Propellant mass	156,400 kg (344,800 lb)	16,780 kg (37,800 lb)		
Thrust	Booster: 1,854 kN (416,000 lb) sea level Sustainer: 266 kN (59,800 lb) sea level SRBs: 433.7 kN (97,500 lb) each	185.2 kN (41,635 lb)		3,000 kN (676,200 lb)

Table 2–69. Atlas IIAS Characteristics[a] *(Continued)*

	Atlas IIAS Stage	Centaur IIAS Upper Stage	Payload Fairing	Total
Nominal burn time	Booster: 163 sec Sustainer: 289 sec	370 sec		
Max. payload	6,192 kg (15,900 lb) to 7,360 kg (19,000 lb) to low-Earth orbit depending on launch inclination; 3,719 kg (8,200 lb) to geosynchronous transfer orbit			
Contractors	Rocketdyne Thiokol: SRBs	Pratt & Whitney		Lockheed Martin

[a] Isakowitz, et al., *International Reference Guide to Space Launch Systems*, 3rd ed., pp. 54, 68–73. Also, International Launch Services, *Atlas Launch System Mission Planner's Guide, Rev. 7* (December 1998), pp. 1–6, A–9.

Table 2–70. Conestoga 1620 Characteristics[a]

	Booster Solid Rocket Motor Stage	Upper Stage	Payload Fairing	Total
Length	30 ft (9.12 m)	6.8 ft (2.07 m)	16 ft (4.88 m)	50 ft (15.24 m)
Diameter	3.3 ft (1.0 m)	4.1 ft (1.25 m)	72 in (1.83 m)	
Gross mass	Each: 25,100 lb (11,400 kg)	4,765 lb (2,161 kg)	Varies	192,700 lb (87.407 kg)
Propulsion	Two Castor IVA and four Castor IVB strap-on motors plus one Castor IVB core strap-on motor	Star 48V motor		
Propellant	Hydroxyl-terminated polybutadiene (HTPB)[b]	HTPB		
Propellant mass	Each: 22,300 lb (10,100 kg)	4,430 lb (2,010 kg)		
Thrust	Each: 111,000 lb (493,700 kN)	15,355 lb (68,300 N)		355,600 lb (1,581 kN)
Max. payload	5,000 lb to low-Earth orbit			
Contractors	Thiokol	Thiokol		EER Systems

[a] Isakowitz and Samella, *International Reference Guide to Space Launch Systems*, 2nd ed., pp. 221–224.

[b] This definition of HTPB as hydroxyl-terminated polybutadiene comes from the NASA Kennedy Space Center acronym list at *www.ksc.nasa.gov/facts/acronyms.html*. Other reliable acronym lists, including the NASA Scientific and Technical Information acronym list (*http://www.sti.nasa.gov/acronym/h.html*) define HTPB as hydroxy-terminated polybutadiene.

Table 2–71. Delta Launches (1989–1998)[a]

Delta Mission No.	Mission	Launch Date (GMT)	Vehicle Type	Comments
184	NAVSTAR II-1 GPS	February 14, 1989	Delta II/6925	Global Positioning System (GPS). First Delta II launch.
183	SDI Delta Star	March 24, 1989	Delta/3920-8	Last Delta 3920 launch.
185	NAVSTAR II-2 GPS	June 10, 1989	Delta II/6925	Second Block II NAVSTAR GPS satellite.
186	NAVSTAR II-3 GPS	August 18, 1989	Delta II/6925	Third Block II NAVSTAR GPS satellite.
187	BSB-R1	August 27, 1989	Delta/4925-8	Launched for British Satellite Broadcasting. First commercial licensed NASA U.S. space launch.
188	NAVSTAR II-4 GPS	October 21, 1989	Delta II/6925	Fourth Block II NAVSTAR GPS satellite.
189	COBE	November 18, 1989	Delta/5920	Cosmic Background Explorer. Last NASA-owned Delta.
190	NAVSTAR II-5 GPS	December 11, 1989	Delta II/6925	Fifth Block II NAVSTAR GPS satellite.
191	NAVSTAR II-6 GPS	January 24, 1990	Delta II/6925	Sixth Block II NAVSTAR GPS satellite.
192	SDI-LACE/RME (LOSAT)	February 14, 1990	Delta II/6920-8	Part of Strategic Defense Initiative program testing.
193	NAVSTAR II-7 GPS	March 26, 1990	Delta II/6925	Seventh Block II NAVSTAR GPS satellite.
194	Palapa B-2R	April 13, 1990	Delta II/6925-8	Indonesian communications satellite.
195	ROSAT	June 1, 1990	Delta II/6920-10	Röentgen Satellite. Joint German, U.S., and British space science mission.
196	INSAT-1D	June 12, 1990	Delta/4925-8	Indian communications and weather satellite. Last Delta I launch.
197	NAVSTAR II-8 GPS	August 2, 1990	Delta II/6925	Eighth Block II NAVSTAR GPS satellite.
198	BSB-R2 (Thor 1)	August 18, 1990	Delta II/6925	Launched for British Satellite Broadcasting.

Table 2–71. Delta Launches (1989–1998)[a] (Continued)

Delta Mission No.	Mission	Launch Date (GMT)	Vehicle Type	Comments
199	NAVSTAR II-9 GPS	October 1, 1990	Delta II/6925	Ninth Block II NAVSTAR GPS satellite.
200	INMARSAT-2 (F1)	October 30, 1990	Delta II/6925	International Maritime Satellite Organization.
201	NAVSTAR II-10 GPS	November 26, 1990	Delta II/7925	First Delta 7925. Tenth Block II NAVSTAR GPS satellite.
202	NATO IV-A	January 8, 1991	Delta II/7925	Military communications satellite.
203	INMARSAT-2 (F2)	March 8, 1991	Delta II/6925	International Maritime Satellite Organization.
204	ASC-2	April 13, 1991	Delta II/7925	Communications satellite.
205	Aurora II	May 29, 1991	Delta II/7925	Communications satellite.
206	NAVSTAR II-11 GPS and LOSAT-X	July 4, 1991	Delta II/7925	Eleventh Block II NAVSTAR GPS satellite and DOD mission.
207	NAVSTAR II-12 GPS	February 23, 1992	Delta II/7925	Twelfth Block II NAVSTAR GPS satellite.
208	NAVSTAR II-13 GPS	April 10, 1992	Delta II/7925	Thirteenth Block II NAVSTAR GPS satellite.
209	Palapa B4	May 14, 1992	Delta II/7925-8	Indonesian communications satellite.
210	EUVE	June 7, 1992	Delta II/6920-10	Extreme Ultraviolet Explorer.
211	NAVSTAR II-14 GPS	July 7, 1992	Delta II/7925	Fourteenth Block II NAVSTAR GPS satellite.
212	1) Geotail, 2) DUVE	July 24, 1992	Delta II/6925	1) Joint NASA-Japanese Institute of Space and Astronomical Science mission; 2) DUVE (Diffuse Ultraviolet Experiment) was attached to the 2nd stage.
213	SATCOM C-4	August 31, 1992	Delta II/7925	Comsat.

Table 2–71. Delta Launches (1989–1998)[a] (Continued)

Delta Mission No.	Mission	Launch Date (GMT)	Vehicle Type	Comments
214	NAVSTAR II-15 GPS	September 9, 1992	Delta II/7925	Fifteenth Block II NAVSTAR GPS satellite.
215	DFS 3 Kopernikus	October 12, 1992	Delta II/7925	Communications satellite launched by McDonnell Douglas for Germany.
216	NAVSTAR II-16 GPS	November 22, 1992	Delta II/7925	Sixteenth Block II NAVSTAR GPS satellite.
217	NAVSTAR II-17 GPS	December 18, 1992	Delta II/7925	Seventeenth Block II NAVSTAR GPS satellite.
218	NAVSTAR II-18 GPS	February 3, 1993	Delta II/7925	Eighteenth Block II NAVSTAR GPS satellite.
219	NAVSTAR II-19 GPS and SEDS-1	March 30, 1993	Delta II/7925	Nineteenth Block II NAVSTAR GPS satellite and Small Expendable Deployer System tether experiment.
220	NAVSTAR II-20 GPS	May 13, 1993	Delta II/7925	Twentieth Block II NAVSTAR GPS satellite.
221	NAVSTAR II-21 GPS and PMG	June 26, 1993	Delta II/7925	Twenty-first Block II NAVSTAR GPS satellite and Plasma Motor Generator was tethered to the 2nd stage.
222	NAVSTAR II-22 GPS	August 30, 1993	Delta II/7925	Twenty-second Block II NAVSTAR GPS satellite.
223	NAVSTAR II-23 GPS	October 26, 1993	Delta II/7925	Twenty-third Block II NAVSTAR GPS satellite.
224	NATO IVB	December 8, 1993	Delta II 7925	Military communications satellite. Launched commercially by McDonnell Douglas.
225	Galaxy I-R	February 19, 1994	Delta II/7925-8	Communications satellite launched commercially by McDonnell Douglas.

Table 2–71. *Delta Launches (1989–1998)*[a] *(Continued)*

Delta Mission No.	Mission	Launch Date (GMT)	Vehicle Type	Comments
226	NAVSTAR II-24 GPS and SEDS-2	March 10, 1994	Delta II/7925	Twenty-fourth Block II NAVSTAR GPS satellite and SED-2 tether experiment.
227	Wind	November 1, 1994	Delta II/7925-10	International Solar Terrestrial Physics/ Global Geospace Science program.
228	Koreasat-1	August 5, 1995	Delta II/7925	Partial failure; booster failed to separate.[b]
229	RADARSAT and SURFSAT	November 4, 1995	Delta II/7920-10	Canadian remote sensing mission and Student Undergraduate Research Fellowship Satellite.
230	RXTE	December 30, 1995	Delta II/7920-10	Rossi X-ray Timing Explorer.
231	Koreasat-2	January 14, 1996	Delta II/7925	Korean communications satellite.
232	NEAR	February 17, 1996	Delta II/7925-8	Near Earth Asteroid Rendezvous.
233	Polar	February 24, 1996	Delta II/7925-10	Space physics satellite.
234	NAVSTAR II-25 GPS	March 28, 1996	Delta II/7925	Twenty-fifth Block II NAVSTAR GPS satellite.
235	Middlecourse Space Experiment (MSX)	April 24, 1996	Delta II/7920-10	USA 118.
236	Galaxy IX	May 24, 1996	Delta II/7925-8	Commercial communications satellite.
237	NAVSTAR II-26 GPS	July 16, 1996	Delta II/7925	Twenty-sixth Block II NAVSTAR GPS satellite.
238	NAVSTAR II-27 GPS	September 12, 1996	Delta II/7925	Twenty-seventh Block II NAVSTAR GPS satellite.
239	Mars Global Surveyor	November 7, 1996	Delta II/7925	Remote sensing mission of Mars.
240	Mars Pathfinder	December 4, 1996	Delta II/7925	Planetary spacecraft with rover.

Table 2–71. Delta Launches (1989–1998)[a] (Continued)

Delta Mission No.	Mission	Launch Date (GMT)	Vehicle Type	Comments
241	GPS BIIR-01 (NAVSTAR 2R-1)	January 17, 1997	Delta II/7925	Failed due to split in the casing of one of the solid rocket motors.
242	MS-1 Iridium® (5 satellites)	May 5, 1997	Delta II/7920-10C	Communications satellites.
243	Thor II	May 20, 1997	Delta II/7925	Norwegian communications satellite.
244	MS-2 Iridium® (5 satellites)	July 9, 1997	Delta II/7920-10C	Communications satellites.
245	NAVSTAR GPS-IIR2	July 23, 1997	Delta II/7925	Block IIR NAVSTAR GPS satellite.
246	MS-3 Iridium® (5 satellites)	August 21, 1997	Delta II/7920-10C	Communications satellites.
247	Advanced Composition Explorer (ACE)	August 25, 1997	Delta II/7920-8	Space science mission.
248	MS-4 Iridium® (5 satellites)	September 27, 1997	Delta II/7920-10C	Communications satellites.
249	NAVSTAR II-28 GPS	November 6, 1997	Delta II/7925	Twenty-eighth block II NAVSTAR GPS satellite.
250	MS-5 Iridium® (5 satellites)	November 9, 1997	Delta II/7920-10C	Communications satellites.
251	MS-6 Iridium® (5 satellites)	December 20, 1997	Delta II/7920-10C	Communications satellites.
252	Skynet 4D	January 10, 1998	Delta II/7925	British military communications satellite.
253	Globalstar-1 (4 satellites Space Systems/Loral)	February 14, 1998	Delta II/7420	Communications satellites.

Table 2–71. Delta Launches (1989–1998)[a] (Continued)

Delta Mission No.	Mission	Launch Date (GMT)	Vehicle Type	Comments
254	MS-7 Iridium® (5 satellites)	February 18, 1998	Delta II/7920-10C	Communications satellites.
255	MS-8 Iridium® (5 satellites)	March 30, 1998	Delta II/7920-10C	Communications satellites.
256	Globalstar-2 (4 satellites Space Systems/Loral)	April 24, 1998	Delta II/7420-10C	British military communications satellites.
257	MS-9 Iridium® (5 satellites)	May 17, 1998	Delta II/7920-10C	Communications satellites.
258	Thor III	June 10, 1998	Delta II/7925	European communications satellite.
259	Galaxy X	August 27, 1998	Delta III/8930	Failed. Exploded 80 seconds after liftoff. First Delta III launch.
260	MS-10 Iridium® (5 Satellites)	September 8, 1998	Delta II/7920-10C	Communications satellites.
261	Deep Space 1 and Sedsat	October 24, 1998	Delta II/7326[c]	New Millennium Program and Students for the Exploration and Development of Space Satellite secondary payload.
262	MS-11 Iridium® (5 satellites)	November 6, 1998	Delta II/7920-10C	Communications satellites.
263	BONUM-1	November 22, 1998	Delta II/7925	Russian television satellite.
264	Mars Climate Orbiter	December 11, 1998	Delta II/7425	Interplanetary spacecraft.

[a] "Delta Launch Record," *http://www.boeing.com/defense-space/space/delta/record.htm* (accessed January 31, 2005).

[b] Koreasat-1 was able to achieve orbit. The Delta booster, however, placed the satellite in a lower-than-specified orbit, thus shortening its useful life.

[c] New variant of Delta II that used three solid Alliant GEM-40 strap-ons rather than nine.

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Table 2–72. Delta 3920/PAM-D Characteristics

	Strap-ons (each)[a]	**Stage 1**	**Stage 2**	**Stage 3 (Payload Assist Module)**	**Total**
Length	9.07 m (30 ft)	22.8 m (75 ft) (includes second stage)	6 m (19.6 ft)	2 m (6.6 ft)	35.5 m (116 ft) including fairing
Diameter	1.02 m (3.3 ft)	2.4 m (8 ft)	2.4 m (8 ft)	1.25 m (4.1 ft)	
Gross mass	10,530 kg (23,215 lb)	85,076 kg (187,560 lb)	6,930 kg (15,331 lb)	1,122 kg (2,474 lb)	
Propulsion	Nine Thiokol Castor IV TX 526-2 strap-on motors	Rocketdyne RS-27 assembly consisting of one RS27 A/B main engine and two LR101-NA-11 vernier engines	Aerojet AJ10-118K engine	Thiokol Star 48 motor	
Propellant	HTPB	Oxidizer: LOX Fuel: RP-1	Aerozine-50 and N_2O_4	HTPB	
Propellant mass	9,373 kg (20,664 lb)	79,380 kg (175,000 lb)	6,004 kg (13,236 lb)	1,909 kg (4,200 lb)	
Avg. Thrust	428 kN (96,218 lb)	1,030 kN (231,553 lb)	44 kN (9,815 lb)	66.6 kN (14,972 lb)	
Nominal burn time	57 sec	224 sec	431 sec	44 sec	
Max. payload	3,045 kg (6,713 lb) to low-Earth orbit; 1,275 kg (2,800 lb) to geosynchronous transfer orbit; 2,135 kg (4,700 lb) to circular sun-synchronous orbit (polar launch)[b]				
Contractors	Thiokol	Rocketdyne	Aerojet	Thiokol	McDonnell Douglas

[a] Jean-Jacques Serra, "Castor," *The Satellite Encyclopedia, http://www.tbssatellite.com/tse/online/lanc_castor.html* (accessed April 7, 2005).

[b] *Aeronautics and Space Report of the President, 1989–1990 Activities* (Washington, DC: National Aeronautics and Space Administration, 1991), p. 160.

Table 2–73. Delta II 6925 Characteristics[a]

	Strap-ons (each)	**Stage 1**	**Stage 2**	**Stage 3 (Payload Assist Module)**	**Total**
Length	11.2 m (36.3 ft)	26.1 m (85.6 ft)	6 m (19.6 ft)	2 m (6.7 ft)	Up to 38.1 m (125 ft) including fairing
Diameter	1.0 m (3.3 ft)	2.44 m (8 ft)	2.44 m (8 ft)	1.25 m (4.1 ft)	
Gross mass	Ground lit: 11,700 kg (25,800 lb) Air lit: 11,900 kg (26,100 lb)	101,700 kg (224,210 lb)	6,997 kg (15,400 lb)	2,141 kg (4,721 lb)	220,000 kg (480,000 lb)
Propulsion	Nine Castor IVA solid rocket motors	Rocketdyne RS-27 assembly consisting of one RS2701A/B main engine and two LR101-NA-11 vernier engines	Aerojet AJ10-118K engine	Thiokol Star 48B motor	
Propellant	HTPB	Oxidizer: LOX Fuel: RP-1	Aerozine-50 and N_2O_4	HTPB	
Propellant mass	10,100 kg (22,300 lb)	96,100 kg (211,900 lb)	6,076 kg (14,400 lb)	2,009 kg (4,430 lb)	
Avg. thrust	427.1 kN (97,700 lb) at sea level 478.3 kN (108,700 lb) vac.	911 kN (204,800 lb) (sea level)	42.4 kN (9,645 lb)	66.4 kN (15,100 lb)	2.620 kN at liftoff (595.000 lb)
Nominal burn time	56.2 sec	265 sec	440 sec	54.8 sec	
Max. payload	5,039 kg (11,100 lb) to low-Earth orbit; 1,819 kg (4,000 lb) to geosynchronous transfer orbit, 3,175 kg (7,000 lb) to sun synchronous orbit[b]				
Contractors	Thiokol	Rocketdyne	Aerojet	Thiokol	McDonnell Douglas

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[a] Isakowitz and Samella, *International Reference Guide to Space Launch Systems,* 2nd ed., pp. 234–237.

[b] *Aeronautics and Space Report of the President, Fiscal Year 1992 Activities,* p. 94.

Table 2–74. Delta 7925 Characteristics[a]

	Strap-on Solid Rocket Motors	**Stage 1**	**Stage 2**	**Stage 3 (Payload Assist Module)**[b]	**Total**
Length	13.0 m (42.5 ft)	26.1 (85.6 ft)	6 m (19.6 ft)	2 m (6.7 ft)	38.2 m–38.9 m (125.2 ft–126.5 ft) depending on fairing
Diameter	1.0 m (3.3 ft)	2.4 m (8 ft)	2.4 m (8 ft)	1.25 m (4.1 ft)	
Gross mass	13,080 kg (28,840 lb) each	101,800 kg (224,400 lb)	6,954 kg (15,331 lb)	2,217 kg (4,887 lb)	231,870 kg (511,190 lb)
Propulsion	Nine Hercules GEM 40 solid rocket motors; some configurations used three or four motors	Rocketdyne RS-27 assembly consisting of one RS27A/B main engine and two LR101-NA-11 vernier engines	Aerojet AJ10-118K engine	Thiokol Star 48B motor	
Propellant	HTPB	Oxidizer: LOX Fuel: RP-1	Aerozine-50 and N_2O_4	HTPB	
Propellant mass	11,765 kg (25,940 lb)	96,100 kg (211,900 lb)	6,004 kg (13,236 lb)	2,009 kg (4,430 lb)	
Avg. thrust	Sea level: 446 kN (100,300 lb); air-lit: 516.2 kN (116,100 lb) each	890 kN (200,000 lb) (sea level)	44 kN (9,815 lb)	66.4 kN (14,927 lb)	3,110 kN (699,250 lb) at liftoff
Nominal burn time	63.3 sec	261 sec	431 sec	87.1 sec	
Max. payload	3,895 kg (8,590 lb) to 5,140 kg (11,330 lb) to low-Earth orbit depending on launch inclination; 3,220 kg (7,100 lb) to Sun-synchronous orbit; 1,870 kg (4,120 lb) to geosynchronous transfer orbit				
Contractors	Alliant Techsystems	Rocketdyne	Aerojet	Thiokol	McDonnell Douglas

[a] Isakowitz et al., *International Reference Guide to Space Launch Systems,* 3rd ed., pp. 112, 115–118.

[b] No PAM upper stage was used for low-Earth orbit missions.

Table 2–75. Representative Delta II Mission Profile Events

Event	Mission Elapsed Time (sec)
Main engine and six solid motors ignited, liftoff	0.0
Mach 1	32.4
Maximum dynamic pressure	49.7
Solid motor burnout (6 of 9)	56
Solid motor ignition (3 of 9)	59
Jettison 6 solid motors	60/61
Jettison 3 solid motors	118
Stage 1 main engine cutoff (MECO)	265
Stage 1-2 separation	271.4
Stage 2 ignition	278
Payload fairing jettison	298
Stage 2 engine first cutoff 1 (SECO 1)	687
Stage 2 restart ignition	1263
Second cutoff–Stage 2 (SECO 2)	1286
Stage 2-3 separation	1300
Stage 3/PAM ignition	1376
Stage 3/PAM burnout	1463
Spacecraft separation	1576

Table 2–76. Pegasus Launches (1989–1998)

Launch Date	Vehicle Model	Customer(s)	Payload	Type of Mission
April 5, 1990	Standard	NASA, DOD	PegSat, USA 55 (SECS)	Flight test instrumentation and atmospheric research. Navy experimental satellite.
July 7, 1991	Standard with HAPS	DOD	MicroSat 1, 2, 3, 4, 5, 6, and 7	Tactical communications network. Achieved mission objectives at lower orbit than planned.[a]
February 9, 1993	Standard	1) INPE Brazil	1) SCD-1	1) Data communications.
		2) Orbital Sciences Corp.	2) OXP-1	2) Experimental communications satellite.
April 25, 1993	Standard	1) Department of Energy-sponsored	1) ALEXIS	1) Array of Low Energy X-ray Imaging Sensors. Satellite was damaged at launch, delaying communication with ground by six weeks.
		2) Orbital Sciences Corp.	2) OXP-2[b]	2) Experimental communications satellite.
May 19, 1994	Standard with HAPS	DOD	STEP-2	Technology validation. Satellite placed in lower than expected orbit.
June 27, 1994	XL	DOD	STEP-1	Technology validation. Mission failed.
August 3, 1994	Standard	DOD	APEX	Advanced Photovoltaic and Electronic Experiments. Space physics technology validation.
April 4, 1995	Standard (Hybrid)	1) ORBCOMM	1) FM1 & FM2	1) Communications.
		2) NASA	2) MicroLab 1	2) Atmospheric research.
June 22, 1995	XL	DOD	STEP-3	Technology validation. Mission failed.

Table 2–76. Pegasus Launches (1989–1998) (Continued)

Launch Date	Vehicle Model	Customer(s)	Payload	Type of Mission
March 8, 1996	XL	DOD	REX-2	Radiation experiment. Technology validation.
May 16, 1996	Standard (Hybrid)	U.S. Air Force	MSTI-3	Miniature Sensor Technology Integration. Technology validation.
July 2, 1996	XL	NASA	TOMS-EP	Total Ozone Mapping Spectrometer Earth Probe. Atmospheric research.
August 21, 1996	XL	NASA	FAST	Fast Auroral Snapshot Explorer. Space physics research.
November 4, 1996	XL	NASA	SAC-B HETE-1	Space physics research. Spacecraft did not separate from third stage. Mission failed.[c]
April 21, 1997	XL	INTA Spain	MINISAT 01	Space physics research. Spain's first satellite, also release of funeral ashes.[d]
August 1, 1997	XL	Orbital Sciences Corp./ NASA	OrbView-2 (SeaStar)	Ocean color imaging, Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project.
August 29, 1997	XL	DOD	FORTE	Technology validation.
October 22, 1997	XL	DOD	STEP-4	Technology validation.
December 23, 1997	XL with HAPS	ORBCOMM-1	ORBCOMM 5-12	Eight low-Earth orbit communications satellites.
February 25, 1998	XL	1) NASA, 2) Teledesic	1) SNOE, 2) T1	1) Student Nitric Oxide Explorer. 2) Commercial communications satellite.
April 1, 1998	XL	NASA	TRACE	Transition Region and Coronal Explorer. Solar physics.

Table 2–76. Pegasus Launches (1989–1998) (Continued)

Launch Date	Vehicle Model	Customer(s)	Payload	Type of Mission
August 2, 1998	XL with HAPS	ORBCOMM-2	ORBCOMM 13-20	Eight low-Earth orbit communications satellites.
September 23, 1998	XL with HAPS	ORBCOMM-3	ORBCOMM 21-27	Eight low-Earth orbit communications satellites.
October 22, 1998	Standard (Hybrid)	INPE Brazil	SCD-2	Data communications.
December 5, 1998	XL	NASA	SWAS	Submillimeter Wave Astronomy Satellite. Space physics.

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[a] The 356-km by 455-km (192-nmi by 246-nmi) orbit fell short of the planned 720-km (389-nmi) circular orbit because a problem at first stage separation caused a guidance error. Orbital Sciences listed the mission as a “success” and stated that the inclination was on target, allowing mission objectives to be met (*Orbital Sciences Corporation Spacecraft History*, table 2–2, pp. 2–8). The satellites’ customer, the Defense Advanced Research Projects Agency (DARPA), said that the rocket’s guidance system compensated for the low orbit and repositioned the satellites to an elliptical orbit that ensured DARPA’s objectives were met. *Aviation Week & Space Technology*, July 22–July 24, 1991 (NASA History Office Folder 010788). However, other references call it a “failure,” or “partial failure.” (Mark Wade, Astronautix.com, *http://www.astronautix.com/lvs.pegasus.htm* (accessed February 8, 2005)). Also “Launching on Pegasus,” Small Satellites home page, *http://centaur.sstl.co.uk/SSHP/launcher/launch_pegasus.html* (accessed February 8, 2005) and “Pegasus,” *The Satellite Encyclopedia*, *http://tbs-satellite.com/tse/online/lanc_pegasus.html* (accessed February 8, 2005).

[b] This payload is listed on Jonathan’s Space Report, *http://planet4589.org/space/log/launchlog.txt* (accessed February 23, 2005) but does not appear on the Pegasus Mission History list produced by Orbital Sciences: *http://www.orbital.com/SpaceLaunch/Pegasus/pegasus_history.htm* (accessed February 3, 2005). It appears that the payload did not separate from the Pegasus third stage.

[c] SAC-B was unable to deploy its solar arrays because the spacecraft did not separate from the Pegasus third stage due to a battery failure in the Pegasus third stage. HETE remained sealed in the interior of the dual payload support structure. SAC-B solar arrays were deployed via ground commands but were unable to generate enough power to keep the satellite’s batteries charged. Both died due to power failure within days of launch. “SAC-B/HETE Spacecraft No Longer Operational,” *NASA News* Release 96-231, November 7, 1996, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1996/96-231.txt* (accessed February 10, 2005); “Partial Launch Vehicle and Spacecraft Re-enter Earth’s Atmosphere,” Goddard Space Flight Center Top Story, April 4, 2002, updated April 7, 2002, *http://www.gsfc.nasa.gov/topstory/20020401hetereenter.html* (accessed February 10, 2005); “SAC-B” Gunter’s Space Page *http;//skyrocket.de/space/doc_sdat/hete.htm* (accessed February 23, 2005) and “HETE 1, 2,” Gunter’s Space Page *http://space/skyrocket.de/doc_sdat/hete.htm* (accessed April 14, 2006).

[d] Among the 24 capsules of funeral ashes taken aloft and put into orbit from this Pegasus were those of the 1960s icon, Timothy Leary, and Gene Roddenberry, creator of “Star Trek.” Marlise Simons, “A Final Turn-On Lifts Timothy Leary Off,” *New York Times*, April 22, 1997, A1.

Table 2–77. Standard Pegasus Characteristics[a]

	Stage 1	Stage 2	Stage 3	Total
Length	8.9 m (29 ft)	2.3 m (7.5 ft)	1.3 m (4.3 ft)	15.2 m[b] (50 ft)
Diameter	1.28 m (4.2 ft) without 6.7-m (22-ft) wingspan	1.28 m (4.2 ft)	0.97 m (3.2 ft)	
Liftoff mass	13,417 kg (29,579 lb)	3,367 kg (7,423 lb)	897 kg (1,978 lb)	
Propulsion	Orion 50S motor	Orion 50 motor	Orion 38 motor	
Propellant	HTPB	HTPB	HTPB	
Propellant mass	12,160 kg (26,808 lb)	3,024 kg (6,667 lb)	771 kg (1,700 lb)	
Nominal burn time[c]	72.4 sec	73.3 sec	68.4	
Thrust (max. vac.)	580.46 kN (130,493 lb)	138.64 kN (31,168 lb)	35.81 kN (8,050 lb)	
Max. payload[d]	380 kg into 185-km orbit; 280 kg into 185-km polar orbit from Vandenberg Air Force Base; 210 kg into sun-synchronous orbit from Vandenberg Air Force Base			
Contractor	Hercules	Hercules	Hercules	Orbital Sciences

[a] All vehicle characteristics are from *NASA SELVS Pegasus Launch System Payload User's Guide*, Release 2.00 (Orbital Sciences Corporation, June 1994), pp. 2–7, unless otherwise indicated.

[b] "Pegasus Launch Vehicle," Space & Missile Systems Center, Department of the Air Force, *http://www.te.plk.af.mil/factsheet/pegfact.html* (accessed February 8, 2005). Included aft skirt assembly, interstage, and fairing.

[c] At 21°C (70°F).

[d] *Aeronautics and Space Report of the President, Fiscal Year 1994 Activities* (Washington, DC: National Aeronautics and Space Administration, 1995), p. 91.

Table 2–78. Pegasus XL Characteristics[a]

	Stage 1	Stage 2	Stage 3	Total
Length	10.3 m (34 ft)	3.1 m (10.2 ft)	1.3 m (4.3 ft)	16.9 m (55.4 ft) including interstage and fairing
Diameter	1.28 m (4.2 ft) without 6.7-m (22-ft) wingspan	1.28 m (4.2 ft)	1 m (3.3 ft)	
Liftoff mass	16,383 kg (36,118 lb)	43,411 kg (95,705 lb)	896 kg (1,975 lb)	23,130 kg (26,742 lb)
Propulsion	Orion 50S XL motor	Orion 50 XL motor	Orion 38 motor	
Propellant	HTPB	HTPB	HTPB	
Propellant mass	15,014 kg (33,100 lb)	3,925 kg (8,653 lb)	770 kg (1,698 lb)	
Nominal burn time[b]	68.6 sec	69.4 sec	68.5 sec	
Thrust (max. vac.)	726 kN (163,211 lb)	196 kN (44,063 lb)	36 kN (8,093 lb)	
Payload capacity[c]	460 kg (1,014 lb) into 185-km orbit; 350 kg (772 lb) into 185-km polar orbit from Vandenberg Air Force Base; 335 kg (739 lb) into sun-synchronous orbit from Vandenberg Air Force Base			
Contractor	Alliant Techsystems	Alliant Techsystems	Alliant Techsystems	Orbital Sciences
Remarks	All XL launches have taken place from the L-1011 "Stargazer" aircraft			

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[a] *Pegasus User's Guide*, Release 5.0, August 2000 (Orbital Sciences Corporation, 2000), pp. 2–4, *http://www.orbital.com/NewsInfo/Publications/peg-user-guide.pdf* (accessed February 4, 2005).

[b] At 21°C (70°F).

[c] *Aeronautics and Space Report of the President, Fiscal Year 1999 Activities* (Washington, DC: National Aeronautics and Space Administration, 2000), p. 97.

Table 2–79. Scout G1 Characteristics[a]

	Stage 1	Stage 2	Stage 3	Stage 4	Total
Length	9.94 m (32.6 ft)	6.56 m (21.5 ft)	3.28 m (10.8 ft)	1.97 m (6.5 ft)	23 m (75 ft) including transition and payload sections
Diameter	1.01 m (3.3 ft) max.	0.79 m (2.6 ft)	0.75 m (2.5 ft)	0.5 m (1.7 m)	
Launch mass	14,255 kg (31,361 lb)	4,424 kg (9,753 lb)	1,395 kg (3,075 lb)	302 kg (665.8 lb)	
Propulsion	Algol IIIA motor	Castor IIA motor	Antares IIIA motor	Altair IIIA motor	
Propellant	Solid	Solid	Solid	Solid	
Propellant mass	12,684 kg (27,965 lb)	3,762 kg (8,294 lb)	1,286 kg (2,835 lb)	275 kg (606.3 lb)	
Avg. thrust	467.1 kN (105,112 lb)	284.3 kN (63,971 lb)	83.1 kN (18,698 lb)	25.4 kN (5713 lb)	
Nominal burn time	56 sec	35 sec	44 sec	29 sec	
Payload capacity	175 kg (386 lb) to a 185-km (100-nmi) orbit				
Prime Contractor	Vought Corp. (LTV Corp.)				

[a] "Scout–Launch Vehicle," Vought Corp., *http://www.vought.com/heritage/special/html/sscout1.html* (accessed February 9, 2005). "Scout Launch Vehicle Program." Langley Research Center Fact Sheet, last updated November 24, 2004, *http://www.nasa.gov/centers/langley/news/factsheets/Scout.html* (accessed February 9, 2005).

Table 2–80. Scout Launches (1989–1998)

Mission No.	Launch Date	Vehicle Type	Customer(s)	Payload	Comment
212C	May 9, 1990	Scout G1	Reimbursable DOD	MACSAT (Multiple Access Comsat)	Two NAVY/DARPA communications satellites
216C	June 29, 1991	Scout G	DOD	REX	Air Force Radiation Experiment
215C	July 3, 1992	Scout G1	NASA	SAMPEX	Solar, Anomalous and Magnetospheric Particle Explorer, first Small Explorer mission
210C	November 21, 1992	Scout G1	Ballistic Missile Defense Organization and U.S. Air Force	MSTI I (Miniature Sensor Technology Integration)	Atmospheric studies
217C	June 25, 1993	Scout G1	U.S. Air Force	RADCAL	Radar Calibration Satellite
218	May 9, 1994	Scout G1	Ballistic Missile Defense Organization and U.S. Air Force	MSTI II	Tracking and Earth observation studies. Last Scout launch

Table 2–81. Taurus 2210 Characteristics[a]

	Stage 0[b]	Stage 1	Stage 2	Stage 3	Total
Length	12.8 m (41.9 ft)	8.6 m (28.3 ft)	3.1 m (10.1 ft)	1.3 m (4.4 ft)	27.9 m (91.4 ft) including interstage and fairing
Diameter	2.4 m (7.8 ft)	1.3 m (4.2 ft)	1.3 m (4.2 ft)	1.0 m (3.2 ft)	2.4 m (7.8 ft)
Liftoff mass	53,424, kg (117,800 lb)	13,242 kg (29,200 lb)	3,379 kg (7,450 lb)	875 kg (1,930 lb)	73,000 kg (161,000 lb)[c]
Propulsion	Castor 120 motor	Orion 50S-G motor	Orion 50 motor	Orion 38 motor[d]	
Propellant	HTPB	HTPB	HTPB	HTPB	
Propellant mass	49,024 kg (108,100 lb)	12,154 kg (26,800 lb)	3,027 kg (6,674 lb)	771 kg (1,700 lb)	
Thrust (avg. vac.)	1,615 kN (363,087 lb)	471 kN (106,000 lb)	115 kN (25,910 lb)	13.8 kN (7,155 lb)	
Nominal burn time	82.5 sec	72.4 sec	75.1 sec	68.5 sec	
Payload capacity	1,400 kg (3,086 lb) into 185-km orbit (100-nmi); 1,080 kg (2,381 lb) into 185-km (100-nmi) polar orbit from Vandenberg Air Force Base; 255 kg (562 lb) into geosynchronous transfer orbit; 1,020 kg (2,249 lb) into sun-synchronous orbit from Vandenberg Air Force Base[e]				
Contractor	Thiokol	Alliant Techsystems	Alliant Techsystems	Alliant Techsystems	Orbital Sciences Corp.

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[a] *Taurus User's Guide*, Release 3.0 (Orbital Sciences Corporation, September 1999), pp. 2–5, *http://www.orbital.com/NewsInfo/Publications/taurus-user-guide.pdf* (accessed February 9, 2005). Liftoff masses and total length were not available from the *Taurus User's Guide* and were obtained from Isakowitz et al., *International Reference Guide to Space Launch Systems*, 3rd ed., pp. 440–441.

[b] The first stage was known as "Stage 0."

[c] Included interstage and fairing.

[d] This stage could be replaced by a spin-stabilized upper stage using Thiokol's Star 37FM perigee kick motor for insertion into geosynchronous transfer orbit.

[e] *Aeronautics and Space Report of the President, Fiscal Year 1999 Activities*, p. 97.

Table 2–82. Taurus Launches (1989–1998)

Launch Vehicle	Launch Date	Mission	Comments
Taurus ARPA	March 13, 1994	STEP-0 (USA-101), Darpasat (USA-102)	DOD mission
Taurus 2210	February 10, 1998	1) Celestis 2 2) Geosat Follow-on (GFO) 3) ORBCOMM FM-3, FM-4	1) funeral ashes disposal 2) military Earth science 3) communications satellite
Taurus ARPA	October 3, 1998	STEX, ATEX (USA-141)	DOD mission

Table 2–83. Titan Launches (1989–1998)

Titan Launch Vehicle	Launch Date (GMT)	Mission	Comments
34D	May 10, 1989	USA 37	DOD satellite.
IV	June 14, 1989	USA 39	Defense Support Program satellite. IUS booster.
34D	September 4, 1989	USA 43, 44	Defense Satellite Communications System payload.
II	September 6, 1989	USA 45	DOD satellite.
III	January 1, 1990	Skynet 4A/JCSat 2	U.K. defense communications satellite/Japanese communications satellite. First commercial Titan III launch.
III	March 14, 1990	Intelsat 6 F-3	International communications satellite. Second stage reached correct orbit but failed to deploy payload. Satellite separated itself from kick stage and was rescued and reboosted by astronauts on STS-49 mission in May 1992.[a]
IVA	June 8, 1990	USA 59, 60, 61, 62	DOD satellite.
III	June 23, 1990	Intelsat 6 F-4	International communications satellite.
IVA	November 13, 1990	USA 65	DOD satellite. IUS booster.
IVA	March 8, 1991	USA 69	DOD satellite.
IVA	November 8, 1991	USA 72, 74, 76, 77	DOD satellite.
II	April 25, 1992	USA 81	DOD satellite.
III	September 25, 1992	Mars Observer	NASA space science mission launched by refurbished Titan ICBM. Transfer orbit kick stage.
IVA	November 28, 1992	USA 86	DOD satellite.
IVA	August 2, 1993	USA	DOD satellite. Failed. Explosion destroyed vehicle.

Table 2–83. Titan Launches (1989–1998) (Continued)

Titan Launch Vehicle	Launch Date (GMT)	Mission	Comments
II	October 5, 1993	Landsat-6	Earth science mission launched by refurbished Titan ICBM. Failed to achieve orbit due to a ruptured hydrazine manifold that stopped fuel from reaching the satellite's stabilizing engines, preventing its ability to attain a stable orbit.
II	January 25, 1994	Clementine	DOD satellite.
IVA	February 7, 1994	Milstar	Military communications satellite. First Titan IV with Centaur upper stage.
IVA	May 3, 1994	DSP	Defense Support Program satellite. Centaur upper stage.
IVA	August 27, 1994	USA 105	DOD satellite. Centaur upper stage.
IVA	December 22, 1994	USA 107	Defense Support Program satellite. IUS booster.
IVA	May 14, 1995	USA 110	DOD satellite.
IVA	July 10, 1995	USA 112	DOD satellite. Centaur upper stage.
IVA	November 6, 1995	USA 115	Military communications satellite. Centaur upper stage.
IVA	December 5, 1995	USA 116	Military reconnaissance.
IVA	April 24, 1996	USA 118	DOD satellite. Centaur upper stage.
IVA	May 12, 1996	USA 119, 120, 121, 122, 123, 124	DOD satellite.
IVA	July 3, 1996	USA 125	Military reconnaissance.
IVA	December 20, 1996	USA 129	DOD satellite.
IVB	February 23, 1997	USA 130	First Titan IVB launch. DOD satellite. IUS booster.
II	April 4, 1997	USA 131, DMSP F14	DOD satellite.
IVB	October 15, 1997	Cassini/Huygens	NASA space science mission. Centaur upper stage.

Table 2–83. Titan Launches (1989–1998) (Continued)

Titan Launch Vehicle	Launch Date (GMT)	Mission	Comments
IVA	October 24, 1997	USA 133	DOD satellite. Centaur upper stage.
IVA	November 8, 1997	USA 136	DOD satellite. Centaur upper stage.
IVB	May 8, 1998	USA 139	Military reconnaissance. Centaur upper stage.
II	May 13, 1998	NOAA-15	NOAA meteorological satellite.
IVA	August 12, 1998	USA	DOD satellite. Centaur upper stage. Last Titan IVA launch. Failed.

[a] Isakowitz et al., *International Reference Guide to Space Launch Systems*, 3rd ed., p. 453.

Table 2–84. Titan II Characteristics[a]

	Stage 1	**Stage 2**
Length	70 ft (21.3 m)	24 ft (7.3 m)
Diameter	10 ft (3.0 m)	10 ft (3.0 m)
Launch mass	269,000 lb (122,016 kg)	65,000 lb (29,484 kg)
Propulsion	Two LR87-AJ-5	One LR 91-AJ-5
Propellant	Aerozine 50, N_2O_4	Aerozine 50, N_2O_4
Propellant mass	260,000 lb (117,934 kg)	59,000 lb (27,215 kg)
Thrust (vac.)	474,000 lb (2,100 kN)	100,000 lb (450 kN)
Nominal burn time	147 sec	182 sec
Payload capacity	4,200 lb (1,905 kg) to polar low-Earth orbit	
Contractor	Aerojet Techsystems (engines) Lockheed Martin (vehicle refurbishment)	

[a] "Titan II Space Launch Vehicle," Fact Sheet, United States Air Force, *http://www.losangeles.af.mil/SMC/PA/Fact_Sheets/ttn2_fs.htm* (accessed February 14, 2005) and Isakowitz et al., *International Reference Guide to Space Launch Systems,* 3rd ed., pp. 457–458.

Table 2–85. Space Shuttle Flights (1989–1998)

Mission	Date	Orbiter	Payload	Comment
STS-29	March 13–March 18, 1989	*Discovery*	Tracking and Data Relay Satellite (TDRS)-4	NASA communications satellite.
STS-30	May 4–May 8, 1989	*Atlantis*	Magellan	First launch of interplanetary spacecraft. Attached to IUS booster.
STS-28	August 8–August 13, 1989	*Columbia*	DOD payload	
STS-34	October 18–October 23, 1989	*Atlantis*	Galileo	Attached to IUS booster, deployed on trajectory toward Jupiter. Space science mission.
STS-33	November 23–November 26, 1989	*Discovery*	DOD payload	
STS-32	January 9–January 20, 1990	*Columbia*	DOD communications satellite Syncom IV-5	Also retrieved the Long Duration Exposure Facility.
STS-36	February 28–March 4, 1990	*Atlantis*	DOD payload	
STS-31	April 24–April 29, 1990	*Discovery*	Hubble Space Telescope	First "Great Observatory." Space science mission.
STS-41	October 6–October 10, 1990	*Discovery*	European Space Agency-sponsored Ulysses	Attached to IUS and Payload Assist Module S (PAM-S) boosters.
STS-38	November 15–20, November 1990	*Atlantis*	DOD payload	
STS-35	December 2–December 11, 1990	*Columbia*	No deployed payload	Astro-1 Spacelab mission.
STS-37	April 5–April 11, 1991	*Atlantis*	Gamma Ray Observatory	Second "Great Observatory." Space science mission.

Table 2–85. Space Shuttle Flights (1989–1998) (Continued)

Mission	Date	Orbiter	Payload	Comment
STS-39	April 28–May 6, 1991	*Discovery*	Deployed and retrieved Strategic Defense Initiative Organization's Infrared Background Signature Survey experiment, mounted on the Shuttle Pallet Satellite (SPAS)-II platform	First unclassified DOD-dedicated Space Shuttle mission.
STS-40	June 5–June 14, 1991	*Columbia*	No deployed payload	Life sciences mission.
STS-43	August 2–August 11, 1991	*Atlantis*	TDRS-5	NASA communications satellite.
STS-48	September 12–September 18, 1991	*Discovery*	Upper Atmosphere Research Satellite	Earth science mission.
STS-44	November 25–December 1, 1991	*Atlantis*	Defense Support Program Satellite	
STS-42	January 22–January 30, 1992	*Discovery*	No deployed payload	International Microgravity Laboratory (IML)-1.
STS-45	March 24–April 2, 1992	*Atlantis*	No deployed payload	Atmospheric Laboratory for Applications and Science (ATLAS)-1.
STS-49	May 2–May 16, 1992	*Endeavour*	Captured and redeployed Intelsat VI satellite after repair	First flight of *Endeavour*.
STS-50	June 25–July 9, 1992	*Columbia*	No deployed payload	U.S. Microgravity Laboratory (USML)-1.
STS-46	July 31–August 8, 1992	*Atlantis*	European Space Agency European Retrievable Carrier (EURECA)	Also deployed tethered Italian satellite, which did not deploy as planned.

Table 2–85. Space Shuttle Flights (1989–1998) (Continued)

Mission	Date	Orbiter	Payload	Comment
STS-47	September 12–September 20, 1992	*Endeavour*	No deployed payload	Spacelab-J (First Japanese Spacelab).
STS-52	October 22–November 1, 1992	*Columbia*	Laser Geodynamic Satellite II	Joint U.S.-Italy mission. Also U.S. Microgravity Payload (USMP)-1.
STS-53	December 2–December 9, 1992	*Discovery*	DOD payload	Last classified payload.
STS-54	January 13–January 19, 1993	*Endeavour*	TDRS-6	NASA communications satellite.
STS-56	April 8–April 17, 1993	*Discovery*	Deployed and retrieved Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN)-201	Also ATLAS-2 science mission.
STS-55	April 26–May 6, 1993	*Columbia*	No deployed payload	German Spacelab D-2.
STS-57	June 21– July 1, 1993	*Endeavour*	Retrieved EURECA	Also commercial SPACEHAB laboratory.
STS-51	September 12–September 22, 1993	*Discovery*	1) Advanced Communications Technology Satellite (ACTS), 2) Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph (ORFEUS)-SPAS deployed and retrieved	
STS-58	October–18 November 1, 1993	*Columbia*	No deployed payload	Spacelab life sciences mission.
STS-61	December 2–December 13, 1993	*Endeavour*	Hubble Space Telescope retrieved and redeployed	First Hubble servicing mission.

Table 2–85. Space Shuttle Flights (1989–1998) (Continued)

Mission	Date	Orbiter	Payload	Comment
STS-60	February 3–February 11, 1994	*Discovery*	Deployed two payloads from Get Away Special (GAS) canisters	SPACEHAB mission. Wake Shield Facility-1 not deployed as planned.
STS-62	March 9–March 19, 1994	*Columbia*	No deployed payload	1) USMP-2, 2) Office of Aeronautics and Space Technology (OAST)-2 experiments.
STS-59	April 9–April 20, 1994	*Endeavour*	No deployed payload	Space Radar Laboratory (SRL)-1.
STS-65	July 9–July 23, 1994	*Columbia*	No deployed payload	Last *Columbia* mission before scheduled modification and refurbishment. Carried IML-2.
STS-64	September 9–September 20, 1994	*Discovery*	Deployed and retrieved SPARTAN-201	Also LIDAR In-Space Technology Experiment.
STS-68	September 30–October 11, 1994	*Endeavour*	No deployed payload	SRL-2.
STS-66	November 3–November 14, 1994	*Atlantis*	Deployed and retrieved German Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA)-SPAS	Also ATLAS-3 science mission.
STS-63	February 3–February 11, 1995	*Discovery*	Deployed and retrieved SPARTAN-204	Performed approach and fly-around of *Mir*. Also SPACEHAB mission.
STS-67	March 2–March 18, 1995	*Endeavour*	No deployed payload	Astro-2 mission.
STS-71	June 27–July 6, 1995	*Atlantis*	No deployed payload	100th U.S. human spaceflight. Docked with *Mir*.
STS-70	July 13–July 22, 1995	*Discovery*	TDRS-7	NASA communications satellite. Last TDRS deployed.

Table 2–85. Space Shuttle Flights (1989–1998) (Continued)

Mission	Date	Orbiter	Payload	Comment
STS-69	September 7–September 18, 1995	*Endeavour*	Deployed and retrieved SPARTAN 201 and Wake Shield Facility-2	First dual deployment and retrieval.
STS-73	October 20–November 5, 1995	*Columbia*	No deployed payload	USML-2.
STS-74	November 12– November 20, 1995	*Atlantis*	No deployed payload	Docked with *Mir.*
STS-72	January 11–January 20, 1996	*Endeavour*	Deployed and retrieved SPARTAN OAST flyer	Also captured and returned Japanese satellite.
STS-75	February 22–March 7, 1996	*Columbia*	Deployed tethered satellite (3-day duration before tether broke)	USMP-3.
STS-76	March 22–March 30, 1996	*Atlantis*	No deployed payload	Docked with *Mir.*
STS-77	May 19–May 29, 1996	*Endeavour*	Deployed and retrieved SPARTAN-207/Inflatable Antenna Experiment	Commercial SPACEHAB mission.
STS-78	June 20–July 7, 1996	*Columbia*	No deployed payload	Life and Microgravity Spacelab.
STS-79	September 19–September 26, 1996	*Atlantis*	No deployed payload	Docked with *Mir.*
STS-80	November 19–December 7, 1996	*Columbia*	Deployed and retrieved ORFEUS-SPAS and Wake Shield Facility-3	
STS-81	January 12–January 22, 1997	*Atlantis*	No deployed payload	Docked with *Mir.*
STS-82	February 11–February 21, 1997	*Discovery*	Retrieved and redeployed Hubble Space Telescope	Second Hubble servicing mission.
STS-83	April 4–April 8, 1997	*Columbia*	No deployed payload	Microgravity Science Laboratory-1 (MSL-1) postponed.

Table 2–85. Space Shuttle Flights (1989–1998) (Continued)

Mission	Date	Orbiter	Payload	Comment
STS-84	May 15–May 24, 1997	*Atlantis*	No deployed payload	Docked with *Mir.*
STS-94	July 1–July 17, 1997	*Columbia*	No deployed payload	Reflight of MSL-1.
STS-85	August 7–August 19, 1997	*Discovery*	Deployed and retrieved German CRISTA-SPAS-2	
STS-86	September 25–October 6, 1997	*Atlantis*	No deployed payload	Docked with *Mir.*
STS-87	November 19–December 5, 1997	*Columbia*	Deployed and retrieved SPARTAN-201	Also USMP-4 Spacelab.
STS-89	January 22–January 31, 1998	*Endeavour*	No deployed payload	Docked with *Mir.*
STS-90	April 17–May 3, 1998	*Columbia*	No deployed payload	Final scheduled flight of Spacelab. Neurolab mission.
STS-91	June 2–June 12, 1998	*Discovery*	No deployed payload	Docked with *Mir.*
STS-95	October 29–November 7, 1998	*Discovery*	Deployed and retrieved SPARTAN-201	Also SPACEHAB module. Carried Hubble Orbiting Systems Test (HOST) platform. John Glenn flight.
STS-88	December 4–December 15, 1998	*Endeavour*	Satelite de Aplicaciones Cientifico (SAC)-A for Argentina	First Space Station mission.

Table 2–86. External Tank Characteristics[a]

Component	Characteristics
Propellants	LOX/LH_2
Length	153.8 ft (46.9 m)
Diameter	27.6 ft (8.4 m)
Gross liftoff weight	1,655,600 lb (760,947 kg)
Inert weight of lightweight tank	66,000 lb (29,937 kg)
Inert weight of super lightweight tank[b]	58,500 lb (26,535 kg)
Liquid oxygen max. weight	1,361,936 lb (617,764 kg)
Liquid oxygen tank weight (empty)	12,000 lb (5,443 kg)
Liquid oxygen tank volume	19,563 cu ft (553,963 liters)
Liquid oxygen tank length	49.3 ft (15 m)
Liquid oxygen tank diameter	27.6 ft (8.4 m)
Liquid hydrogen max. weight	227,641 lb (103,256 kg)
Liquid hydrogen tank diameter	27.6 ft (8.4 m)
Liquid hydrogen tank length	96.7 ft (29.5 m)
Liquid hydrogen tank volume	53,518 cu ft (1,515,461 liters)
Liquid hydrogen tank weight (empty)	29,000 lb (13,154 kg)
Intertank length	22.5 ft (6.9 m)
Intertank diameter	27.6 ft (8.4 m)
Intertank weight	12,100 lb (5,488 kg)
Prime contractor	Martin Marietta/Lockheed Martin since 1994

[a] "External Tank," *NSTS 1988 News Reference Manual*, September 1988, *http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/et.html* (accessed February 25, 2005).

[b] The super lightweight external tank was first used on STS-91 in June 1998. "Super Lightweight External Tank," Space Shuttle Technology Summary, NASA Marshall Space Flight Center, FS-2003-06-70-MSFC, *http://www.nasa.gov/centers/marshall/pdf/100423main_shuttle_external_tank.pdf* (accessed February 25, 2005).

Table 2–87. Solid Rocket Booster Characteristics[a]

Component	Characteristics
Length	149.16 ft (45.5 m)
Diameter	12.17 ft (3.7 m)
Propellant weight (each solid rocket motor)	1,100,000 lb (500,000 kg)
Inert weight (each SRB)	192,000 lb (89,090 kg)
Thrust at launch	3,300,000 lb (14,679 kN)
Propellant mixture	Ammonium perchlorate oxidizer, aluminum fuel, iron oxide, polymer, epoxy

[a] "Solid Rocket Boosters," *NSTS 1988 News Reference Manual,* September 1988, *http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/srb.html* (accessed February 25, 2005).

Table 2–88. Space Shuttle Main Engine Characteristics[a]

Component	Characteristics
Length	14 ft (4.3 m) at nozzle exit
Diameter	7.5 ft (2.3 m) at nozzle exit
Approx. weight (each)	7,000 lb (3,175 kg)
Number of engines	Three on each orbiter
Range of thrust level	65%–109% of rated power level
Thrust (100%)	Each engine: 375,000 lb (1,668 kN) at sea level, 470,000 lbs (2,091 kN) in vacuum
Thrust (109%)	417,300 lb (1,856 kN) at sea level, 513,250 lb (2,283 kN) in vacuum[a]
Operating life	7.5 hours and 55 starts
Propellant	Fuel: LH_2, Oxidizer: LOX, in a 6:1 ratio
Nominal burn time	522 secb[b]
Prime contractor	Boeing Rocketdyne

[a] "Main Propulsion System," *NSTS 1988 News Reference Manual*, September 1988, *http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-mps.html* (accessed February 25, 2005).

[b] Boeing Rocketdyne, the engine manufacturer, lists the maximum thrust of each engine in vacuum at 512,950 lb (2,282 kN).

[b] Isakowitz et al., *International Reference Guide to Space Launch Systems*, 3rd ed., p. 407.

Table 2–89. Titan Centaur Upper Stage Characteristics[a]

Component	Characteristics
Length	29.45 ft (9 m)
Diameter	14.2 ft (4.3 m)
Thrust	33,000 lb (15,000 kg)
Propellants	Cryogenic–Liquid Oxygen and Liquid Hydrogen Stage
Propellant weight	46,000 lb (20,865 kg)
Propulsion	Two Pratt & Whitney restartable RL10 engines
Contractor	Lockheed Martin Space Systems

[a] "Titan," Lockheed Martin, *http://www.lockheedmartin.com/wms/findPage.do?dsp=fec&ci=15525&rsbci=0&fti=0&ti=0&sc=400* (accessed March 17, 2005).

Table 2–90. Inertial Upper Stage Characteristics

Component	Characteristics
Length	17 ft (5.18 m)
Diameter	9.25 ft (2.8 m)
Weight	32,500 lb (14,742 kg)
Propulsion	Two solid-fueled United Technologies motors
Propellant weight	First stage: 21,400 lb (9,797 kg) Second stage: 6,000 lb (2,722 kg)
Thrust	First stage: 42,000 lb (188,496 N) Second stage: 18,000 lb (80,784 N)
Contractor	Boeing

Table 2–91. Inertial Upper Stage Launches

Date	Vehicle	Payload
March 13, 1989	STS-29	Tracking and Data Relay Satellite-4
May 4, 1989	STS-30	Magellan
June 14, 1989	Titan IV	Defense Support Program satellite
September 4, 1989	Titan 34D	Defense Satellite Communications System satellite
October 18, 1989	STS-34	Galileo
November 23, 1989	STS-33	DOD payload
October 6, 1990	STS-41	Ulysses
November 13, 1990	Titan IV	Defense Support Program satellite
August 2, 1991	STS-43	Tracking and Data Relay Satellite-5
November 24, 1991	STS-44	Defense Support Program satellite
January 13, 1993	STS-54	Tracking and Data Relay Satellite-6
December 22, 1994	Titan IV	Defense Support Program satellite
July 13, 1995	STS-70	Tracking and Data Relay Satellite-7
February 24, 1997	Titan IV	Defense Support Program satellite

Table 2–92. DC-X Characteristics[a]

Component	Characteristics
Width	13-1/3 ft (4 m) at base, conical shape
Height	40 ft (12.2 m)
Weight (empty)	20,000 lb (9,072 kg)
Weight (with propellants)	41,600 lb (18,870 kg)
Propellants	LOX and LH_2
Propulsion	Four RL10A5 rocket engines
Thrust	13,500 lb each (60,000 N)
Reaction controls	Four 440 lb (1,957 N)-thrust gaseous oxygen, gaseous hydrogen thrusters
Contractor	McDonnell Douglas

[a] "DC-X Fact Sheet," BMDOLink, Delta Clipper-Experimental Fact Sheet, Office of External Affairs, April 1993, *http://www.hq.nasa.gov/office/pao/History/x-33/dcx-facts.htm* (accessed March 22, 2005).

Table 2–93. DC-X and DC-XA Flight Tests[a]

Flight	Launch Date	Duration (sec)	Altitude (m/ft)	Description
DC-X Test Flights				
1	August 18, 1993	59	46/151	Verified flight control systems and vertical landing capabilities
2	September 11, 1993	65.8	92/302	Ascent and landing mode control and ground effects survey
3	September 30, 1993	72.2	370/1,214	180-degree roll; aerostability data
4	June 20, 1994	135.9	870/2,854	Full propellant load; radar altimeter in control loop
5	June 27, 1994	77.9	790/2,592	In-flight abort after gaseous hydrogen explosion; vehicle demonstrated autoland capabilities
6	May 16, 1995	123.6	1,330/4,364	Continued expansion of flight envelope; constant angle of attack
7	June 12, 1995	132	1,740/5,709	First use of reaction control system thrusters; angle of attack from 0 to 70 degrees
8	July 12, 1995	124	2,500/8,202	Final flight of DC-X; demonstrated turnaround maneuver; aeroshell cracked during 14 ft/sec landing
DC-XA Test Flights				
1	May 18, 1996	62	244/801	First flight of DC-XA; aeroshell caught fire during slow landing
2	June 7, 1996	63.6	590/1,936	Maximum structural stresses with 50 percent full LOX tank
3	June 8, 1996	142	3,14010,302	26-hour rapid turnaround demonstration; new altitude and duration record
4	July 31, 1996	140	1,250/4,101	Landing strut 2 failed to extend; vehicle tipped over and LOX tank exploded; vehicle destroyed

[a] "The Delta Clipper Experimental: Flight Testing Archive," *http://www.hq.nasa.gov/office/pao/History/x-33/dcxfile.htm* (Web site created by Kirk Sorensen) (accessed March 22, 2005).

Table 2–94. X-34 Characteristics[a]

Component	Characteristics
Length	58.3 ft (17.8 m)
Wingspan	27.7 ft (8.4 m)
Weight unfueled	18,000 lb (8,165 kg)
Main propulsion	One NASA (Marshall Space Flight Center)-designed Fastrac engine
Propellant	LOX/RP-1
Propellant weight	30,000 lb (13,600 kg)
Thrust	60,000 lb (27,216 kg)
Nominal burn time	154 sec (without throttling)
Maximum speed	Mach 8
Maximum altitude	Approximately 50 miles (80 km)
Prime contractor	Orbital Sciences Corporation

[a] "X-34 Demonstrating Reusable Launch Vehicle Technologies," Historical Fact Sheet, NASA Marshall Space Flight Center, *http://www.nasa.gov/centers/marshall/news/background/facts/x-34.html* (accessed March 22, 2005).

Table 2–95. X-33 Characteristics[a]

Component	Characteristics
Length	69 ft (21 m)
Width	77 ft (23.5 m)
Takeoff weight	285,000 lb (129,274 kg)
Propellant	LH2/LOX
Fuel weight	210,000 lb (95,254 kg)
Main propulsion	Two J-2S linear aerospike engines
Take-off thrust	410,000 lb (185,973 kg)
Maximum speed	Mach 13+
Contractors	Lockheed Martin (prime) Rocketdyne (engines) Rohr (thermal protection systems) Allied Signal (subsystems) Sverdrup (ground support equipment)

[a] "X-33 Advanced Technology Demonstrator," Historical Fact Sheet, Marshall Space Flight Center, *http://www.nasa.gov/centers/marshall/news/background/facts/x33.html* (accessed March 22, 2005).

Table 2–96. Reusable Launch Vehicle Chronology[a]

Date	Event
1990	Ballistic Missile Defense Organization initiated DC-X program.
August 1991	McDonnell Douglas won a $60 million contract to build the DC-X.
August 18, 1993	Flight tests of DC-X were begun.
January 1994	NASA's Access to Space study released. The study recommended that development of an advanced technology, single-stage-to-orbit, fully reusable rocket launch vehicle become a NASA goal.
February 1994	NASA released a series of NASA Research Announcements to industry for RLV component technology. This program laid the groundwork for technologies to be demonstrated during the X-33 flight program.
May 31, 1994	NASA identified $1 million for the DC-XA test program in addition to $990,000 dollars transferred to the DC-X program earlier in 1994. Enabled acceptance of DC-X vehicle from the Air Force.
June 20, 1994	First flight of DC-X under second phase of program took place.
June 27, 1994	DC-X test demonstrated the vehicle's autoland capabilities.
July 1994	Eighteen cooperative agreements were signed with industry in the areas of structures, thermal protection, and advanced propulsion.
August 5, 1994	President William J. Clinton issued National Space Transportation Policy (NSTC-4) for the RLV Technology program. It called for NASA to formulate an implementation plan by October 5, 1994 for Administration review.
October 31, 1994	NASA's FY 1995 Operating Plan established a new Space Access and Technology Program and funded the RLV program at $93.5 million.
November 7, 1994	The Administration approved the NASA Implementation Plan for the President's National Space Transportation Policy. The plan accelerated the X-33 schedule and called for NASA to select an X-33 technology demonstrator by July 1996.
January 12, 1995	NASA issued two Cooperative Agreement Notices requesting proposals for the development of technology demonstrators for an RLV program.
March 1995	NASA and Orbital Sciences Corporation signed a cooperative agreement for the X-34.

Table 2–96. Reusable Launch Vehicle Chronology[a] (Continued)

Date	Event
March 29, 1995	NASA signed three cooperative Phase I agreements to design the X-33, the next generation space booster. Agreements were signed with Lockheed Advanced Development Company (Skunk Works), McDonnell Douglas Aerospace, and Rockwell International Corporation. NASA provided approximately $7 million to each industry partner, with each investing a matching sum.
May 16, 1995	DC-X test flights were begun in support of NASA's RLV program.
July 7, 1995	Last test flight of DC-X took place. The aeroshell cracked during landing. The vehicle was turned over to NASA and sent to McDonnell Douglas for modifications to the DC-XA.
December 15, 1995	NASA issued a draft Cooperative Agreement Notice for the design, fabrication, and flight test of the X-33 advanced technology demonstrator.
March 1996	The President's FY 1997 budget highlighted that the RLV was a science and technology investment. The RLV was cited as a way to significantly cut the cost of reaching space.
March 1996	NASA issued a new NASA Research Announcement for the X-34.
April 1, 1996	NASA issued a Cooperative Agreement Notice for demonstration of single-stage-to-orbit (SSTO) technologies through the design, fabrication, and flight test of an X-33 advanced technology demonstrator.
May 8, 1996	The DC-XA completed a series of ground tests at the U.S. Army White Sands Missile Range in preparation for flight tests.
May 18, 1996	The DC-XA began a new set of test flights.
June 1996	NASA awarded a contract valued at approximately $50 million to Orbital Sciences Corporation for the X-34.
June 14, 1996	A full-scale segment of a graphite-composite wing designed for an RLV was successfully "tested to failure" at Langley Research Center. This was the first structural test of a full-scale component designed and fabricated to validate the use of graphite-composite primary structures for RLVs. The purpose of the test was to determine the maximum load the wing-box could carry as well as to understand how it would fail.
July 2, 1996	Vice President Al Gore announced at the Jet Propulsion Laboratory in Pasadena, California, that Lockheed Martin had been selected to build the X-33 test vehicle, called VentureStar. Lockheed Martin won the competition for the X-33 Phase II contract over contenders McDonnell Douglas and Rockwell International.

Table 2–96. Reusable Launch Vehicle Chronology[a] *(Continued)*

Date	Event
July 31, 1996	A landing strut on the DC-XA failed to extend. The vehicle tipped over and exploded due to an open pressurant line. The vehicle was destroyed.
October 1, 1996	NASA filed Notice of Intent 96-118 with the Federal Register of its intention to prepare an environmental impact statement (EIS) and to conduct scoping meetings for the development and testing of the X-33 vehicle. The EIS addressed environmental issues associated with fabrication, assembly, testing, and preparation of the flight operations and landing sites associated with the X-33 flight vehicle.
November 13, 1996	Gary Payton, NASA's Director of Space Transportation, and T. K. Mattingly, Vice President for Lockheed Martin's RLV Program, held an informal meeting to discuss the program status and answer questions on the X-33, which was undergoing its Preliminary Design Review that week in California to formalize the engineering baseline of the X-33 vehicle before moving on to the detailed design phase.
November 1, 1996	Langley Research Center conducted thermal-mechanical tests toward the development of a durable, lightweight, cryogenic insulation system for possible use on future RLVs.
December 18, 1996	A three-day Preliminary Design Review (PDR) was completed for the X-33 operations segment and ground systems segment. Individual PDRs already had been conducted on the aerospike engine, the hydrogen tank, the structure, and most subsystems.
January 21, 1997	Langley Research Center issued a press release about X-33 wind tunnel testing during Phase I in the 22-Inch Mach 20 Helium Tunnel at Langley.
January 23, 1997	NASA held a public meeting in Idaho Falls, Idaho, to gather public comment on its plan to conduct flight tests of the X-33. The meeting was part of NASA's EIS process in support of the X-33 program. The formal process had begun on October 7, 1996, after NASA published a Notice of Intent 96-118 in the Federal Register. The Idaho Falls meeting was the 12th NASA public meeting to discuss the potential environmental impact of the X-33 test flights. Earlier meetings were held in towns neighboring proposed takeoff and landing sites in Southern California, Utah, Washington, and Montana.
February 20, 1997	A 7.75 percent scale model of the X-33 completed two weeks of wind tunnel tests in the 5.1-meter transonic wind tunnel at the Air Force's Arnold Engineering Development Center at Arnold Air Force Base, Tullahoma, Tennessee, according to Space Log, March 10 to March 16, 1997.
March 1997	An aluminum and stainless steel model of the X-33 was tested in Langley's Low-Turbulence Pressure Tunnel.

Table 2–96. Reusable Launch Vehicle Chronology[a] (Continued)

Date	Event
March 6, 1997	NASA announced that surveying was underway at Edwards Air Force Base, California, in preparation for the construction of the X-33 launch site. Sverdrup Corporation, the X-33 team's launch facility contractor, was undertaking the surveying of the launch site at Haystack Butte. Construction of the launch pad and facilities was expected to be completed by September 9, 1998. Launch facility activation, which included verification of the launch pad fueling system, was scheduled to be completed by October 1, 1998.
April 10, 1997	NASA announced that an aluminum and stainless steel scale model of the X-33–about 38 cm (15 in) long by 38 cm (15 in) wide–was undergoing extensive wind tunnel testing at Langley's 16-Foot Transonic Tunnel through mid-April 1997.
April 16, 1997	Continuing wind tunnel testing was carried out at Marshall Space Flight Center to correct an X-33 control deficiency at low supersonic speeds (Mach 1 to Mach 2). Adding canards appeared to be the only viable solution to date.
April 30, 1997	Marshall Space Flight Center announced that, it had conducted hot-fire tests of components for the X-33 linear aerospike engine in its Propulsion Laboratory's East Test Area. The test apparatus consisted of three hydrogen-cooled thrust cells constructed to represent a section of the X-33 engine, which was to have two banks of 10 side-by-side thrusters. Test results were to be reviewed with Rocketdyne, which built the test thrust cells and was to build the X-33 aerospike engine.
Mid-April–May 1997	Wind tunnel testing of a scale model X-33 in the Langley's Research Center's Unitary Wind Tunnel at supersonic speeds ranging from Mach 1.5 to Mach 4.5 continued from mid-April to early May. Wind tunnel testing also continued through May at Marshall Space Flight Center.
May 1997	A "tiger team" was working full-time on reducing the dry weight (without fuel) of the X-33 by 5,000 lb (2,268 kg) to 6,000 lb (2,722 kg). The team sorted through more than 400 recommendations of ways to reduce the weight.
May 21, 1997	The "tiger team" working on the X-33 weight problem gave a presentation. Weight reduction recommendations were ranked according to minor, medium, or major cost and schedule impacts. The team indicated that weight could be reduced by about 8,000 lb (3,629 kg) to 11,000 lb (4,990 kg), but the X-33 project costs and schedule would be affected.

Table 2–96. Reusable Launch Vehicle Chronology[a] (Continued)

Date	Event
June 1997	Additional wind tunnel testing of X-33 models took place in Langley's Hypersonic Facilities Complex. Also, X-33 wind tunnel testing started in Langley's 14-by-22-Foot Subsonic Tunnel in mid-June.
June 24, 1997	Aerospace Daily reported that "typical development problems" had led to postponement of the first X-33 test flight from March 1999 to July 1999, and slippage of the Critical Design Review (CDR) from September to an unspecified time in the fall. A critical problem behind the postponement was fabrication of the liquid-hydrogen fuel tank. In addition, Aerospace Daily reported that the Lockheed Martin Skunk Works had consolidated X-33 project management at Palmdale, California, and Jerry Rising had been named Vice President for X-33 and RLVs. Rising replaced T.K. Mattingly, who transferred to Lockheed Martin's aeronautical division at corporate headquarters in Bethesda, Maryland.
June 27, 1997	NASA released the draft EIS.
July 1997	In mid-July, wind tunnel testing of X-33 models in Langley's 14-by-22-Foot Subsonic Tunnel was concluded.
July 3, 1997	Aerospace Daily reported on X-33 progress, based on an interview with Lockheed Martin X-33 Vice President Jerry Rising. The Skunk Works was considering use of a colder, denser cryogenic propellant and had dropped plans to add canards for vehicle stability in the low transonic range (Mach 1 and Mach 2) in favor of changes in the tail structure. Weight growth was under attack by a special "tiger team."
August 1997	A critical series of tests on the X-34 Fastrac engine was successfully completed at Marshall Space Flight Center.
August 26, 1997	The Linear Aerospike SR-71 Experiment was mounted on a NASA SR-71 aircraft at Dryden Flight Research Center, Edwards, California, in preparation for the experiment's first flight, then scheduled for September.
August 26, 1997	Aerospace Daily reported that a gas generator adapted for the X-33 aerospike engine from a J-2 Saturn rocket engine had undergone 14 hot-fire tests at Marshall Space Flight Center.
August 28, 1997	Langley Research Center conducted load tests of a full-scale segment of a composite intertank structure for the X-33 program.

Table 2–96. Reusable Launch Vehicle Chronology[a] (Continued)

Date	Event
September 11, 1997	Aerospace Daily reported on X-33 progress. Five of eight 100-lb (45.4 kg) liquid hydrogen tank panels had been fabricated by Alliant Techsystems in a Utah plant, and tests of the composite seams were proceeding without any surprises. The liquid oxygen tank had been welded together. Removing the turbo alternator removed a "big hunk" of vehicle weight. Cooling the liquid oxygen and hydrogen propellants to temperatures lower than normal cut overall vehicle weight further and allowed the X-33 to carry additional fuel.
September 18, 1997	A two-day CDR of the X-33 thermal protection system by Rohr at its Chula Vista, California, facility ended
September 24, 1997	The two-day CDR of the X-33 aerospike engine (known also as the XRS-2200 engine) ended. The CDR took place at Rocketdyne's DeSoto campus in Chatsworth, California, where the X-33 engines were being designed.
September 26, 1997	NASA released the Final EIS for the X-33 and named the preferred flight testing launch and landing sites.
October 31, 1997	NASA announced that the X-33 had completed the five-day vehicle CDR successful, a major event in X-33 evolution. With completion of the CDR, NASA gave the Lockheed Martin Skunk Works approval to proceed with the fabrication of all remaining components and the assembly of the flight vehicle. The package of CDR technical information contained roughly 2,750 charts in 11 volumes.
October 31, 1997	The first successful flight of the Linear Aerospike SR-71 Experiment (LASRE) at Dryden Flight Research Center took place.
November 4, 1997	NASA completed its Record of Decision on the X-33 EIS and announced an intention to proceed with the preferred X-33 flight test program as described in the Final EIS issued October 3, 1997.
November 14, 1997	Groundbreaking ceremony took place at the future X-33 launch site on Edwards Air Force Base.
January 1998	NASA decided to modify its contract with Orbital Sciences Corporation to provide for a second X-34 flight vehicle. The modification also allowed for additional unpowered tests and more flexibility in demonstrating various technologies.
January 1, 1998	A faulty control system in the X-33 construction hangar set off water canons intended to fight fires. A crew of about a dozen worked on New Year's Eve to dry out the X-33 construction area. No permanent damage resulted, and work continued as usual.

Table 2–96. Reusable Launch Vehicle Chronology[a] *(Continued)*

Date	Event
January 14, 1998	Construction of the X-33 launch site at Haystack Butte progressed. Sverdrup completed rough grading of the launch site. The new road to the launch site was drivable but, like the site, was still at subgrade level.
January 21, 1998	Sverdrup completed rough grading of the X-33 launch site.
February 11, 1998	The first major X-33 component, the liquid oxygen tank, was delivered to the Palmdale, California, hangar where construction of the vehicle was taking place. An Airbus A300-600ST made the delivery.
February 12, 1998	The ground cold flow test of the LASRE was performed. This test included one normal cold flow and one emergency systems cold flow. The emergency systems cold flow tested the effects of control system power loss during flight. The liquid oxygen tank pressurized normally during the first (normal cold flow) test, validating the repair made to the vent system. The emergency test appeared to have been successful. A data review was scheduled for February 18, 1998.
February 25, 1998	A routine X-33 quarterly review took place at Marshall Space Flight Center. Presentations surveyed current progress.
February 25, 1998	Launch site construction continued to progress as all Edwards Air Force Base infrastructure (roads, power, water, and communications) was extended to the site.
March 4, 1998	A NASA SR-71 completed its first cold flow flight as part of the LASRE at Dryden Flight Research Center, Edwards, California.
March 11–March 12, 1998	The NASA Independent Annual Review of the X-33 program took place. X-33 technical and cost performance was surveyed. A final report detailing findings and conclusions was to be briefed to the NASA Program Management Council on April 15, 1998. The review indicated that Lockheed Martin's Skunk Works had addressed many of the concerns that arose during the September 1997 Independent Annual Review. NASA's Gary Payton and Gene Austin were pleased with the review results.
March 20, 1998	During a project review held at the Rocketdyne facility in Canoga Park, California, Rocketdyne made known certain schedule hazards that had developed with two of their suppliers, Weldmac and CFI. It was reported that, in the worst case, aerospike engine deliveries might slip three to five months. Rocketdyne was looking into their suppliers' difficulties to mitigate risk to the program schedule.
April 8, 1998	With the exception of some fastener shortages, the center thrust structure of the X-33 vehicle was now complete.

Table 2–96. Reusable Launch Vehicle Chronology[a] (Continued)

Date	Event
April 19, 1998	The liquid oxygen tank was moved into the main assembly fixture. The move took less than an hour and was completed two days ahead of schedule.
May 18, 1998	NASA's F-15B Aerodynamic Flight Facility fighter aircraft, based at Dryden Flight Research Center, flight-tested thermal protection materials intended for use on the X-33 to determine the durability of the materials, specifically measuring the shear and shock loads to which the materials were exposed. The materials tested included metallic Inconel tiles, soft Advanced Flexible Reusable Surface Isolation tiles, and sealing materials.
June 8, 1998	Aerospace Daily reported that "Lockheed Martin was carrying a 'three-month hazard' on the linear aerospike engine it will need to power the X-33 testbed next summer, but Rocketdyne had developed workarounds and fixes to get the engine back on track," cited Jerry Rising, Lockheed Martin Program Manager.
June 8, 1998	Aerospace Daily reported that leakage into the structure of the subscale aerospike mounted on NASA's SR-71 Blackbird had delayed the first hot-fire test of the engine "a few weeks."
June 8, 1998	Aerospace Daily reported that X-33 Program Manager Jerry Rising and X-34 Program Manager Bob Lindberg threatened to not allow their X vehicles to fly unless Congress passed indemnification legislation protecting them against third-party liability in case of an accident during flight testing.
June 10, 1998	NASA announced that pictures of the X-33 vehicle and launch site, taken every 15 minutes from three digital cameras, would be posted on an Internet site. The images from two cameras would show the vehicle's primary assembly structure, the side-by-side tooling structures for the X-33's upper thermal protection system, and the vehicle's upper internal support structure, while the third camera would focus on the vehicle's launch pad. The vehicle images would not be current, delayed one day.
June 30, 1998	NASA announced completion of the F-15B flight testing of thermal protection materials for the X-33 at Dryden Flight Research Center, Edwards, California. The six flights tested the durability of the materials at hypersonic velocities. The F-15B reached an altitude of 36,000 ft (10,973 M) and a top speed of Mach 1.4. The material samples tested included metallic Inconel tiles, soft Advanced Flexible Reusable Surface Insulation tiles, and sealing materials.

Table 2–96. Reusable Launch Vehicle Chronology[a] *(Continued)*

Date	Event
July 1998	The X-34 program passed a critical milestone as the first wing assembly completed qualification tests and was shipped to Orbital Sciences Corporation and mated to the X-34 test article under construction.
July 6, 1998	Aerospace Daily, in an article titled “Wagons Ho!” reported that the Lockheed Martin Skunk Works had abandoned flying the X-33 back to its launch pad at Edwards Air Force Base in favor of trucking the experimental aircraft overland, “because the Shuttle program won’t give up one of its two Boeing 747s for ferry flights.”
July 22, 1998	Difficulties with fabricating the X-33 liquid hydrogen tanks continued. As a result, delivery dates for the two tanks slipped from July 31 and September 2 to mid-October and mid-November, respectively. The impact of these delays on vehicle assembly was still being assessed.
July 29, 1998	Aerojet recommended to NASA and Lockheed Martin that they use a thruster configuration that included a nozzle made of columbium to correct for the thermal problems that had caused nozzles to burn through in earlier tests. Using columbium nozzle parts would not increase the X-33’s net weight; however, preparing the parts would require a long lead time. To minimize schedule impact, Aerojet proposed delivering the thrusters without nozzles to allow continuation of vehicle assembly and supplying the columbium nozzles at a later date.
August 5, 1998	The X-33 System Architecture Review (SAR) and Optimized Design Review (ODR) were held in Palmdale with representatives from each Skunk Works partner, NASA, and the “Gray Beards” attending. The “Gray Beards” panel of experts was composed mainly of NASA senior personnel led by Del Freeman of Langley Research Center.
August 26, 1998	AlliedSignal delivered the X-33 nose landing gear strut. It was to be modified into the X-33 configuration for a test fit. This same test fit already had been accomplished for the main trunion pivots and the drag link attachments without any problems.

Table 2–96. Reusable Launch Vehicle Chronology[a] (Continued)

Date	Event
September 2, 1998	Spence M. (Sam) Armstrong, recently named NASA Associate Administrator for the Office of Aeronautics and Space Transportation Technology (Code R), revealed a reorganization during a staff briefing that would dilute the responsibilities of Gary Payton, who, as Deputy Associate Administrator for Space Transportation Technology, currently headed the X-33, X-34, and advanced space transportation programs, moving him more into the aeronautics half of the Office. Payton would occupy a lower position, Division Director, under the proposed reorganization, which was scheduled to take place on October 1. Payton had championed single-stage-to-orbit vehicles for many years. The change seriously jeopardized the status of the program within the NASA hierarchy.
September 11, 1998	Aerospace Daily reported that the pending reorganization of NASA's Office of Aeronautics and Space Transportation Technology "raised the hackles" of Rep. Dana Rohrabacher of California, a long-time champion of single-stage-to-orbit technology and chairman of the NASA authorization subcommittee. Rohrabacher expressed his concerns in a letter to NASA Administrator Daniel Goldin.
September 23, 1998	A nine-panel thermal protection system array was test-fitted on the bottom of the X-33 during the previous week by a joint team of B.F. Goodrich and Skunk Works technicians. The metallic panels were equipped with the new secondary seal designs. One panel also was removed from the center of the array to prove that any panel could be replaced.
September 27, 1998	Continuing difficulties with fabrication of the two liquid hydrogen tanks were experienced. A cure cycle was lost during the first doubler installation process on tank #2. The tank was removed early from the cure cycle after blowing a bag at the end of a ramp-up point. The combination of the out time and this cure cycle resulted in an unacceptable strength impact to the bond joints. The doublers were removed over the weekend (September 26–27) and could be replaced with existing materials. Loss of the cure cycle delayed fabrication of tank #2 by 30 days. Construction of the vehicle structure and electronics continued.

Table 2–96. Reusable Launch Vehicle Chronology[a] *(Continued)*

Date	Event
October 2, 1998	The X-33 engine testing program began. At 12:13 a.m. Central Time, the first successful aerospike engine-related test took place at Stennis Space Center. The test intended to calibrate the liquid hydrogen and liquid oxygen fuel turbopumps, check facility settings, and verify valve timing to prime the gas generator. The test lasted 2.81 seconds, and no flaws or anomalies were detected. The tested powerpack hardware consisted of the main power-generating and pumping components of the aerospike engine, including the liquid oxygen and liquid hydrogen turbopumps, a gas generator for the turbopump drive, vehicle connect lines, and interconnecting flight ducts. These powerpack tests were critical to the development of the linear aerospike engine because they allowed various performance levels to be tested in parallel with the design and construction of the engine. Full-scale engine tests were scheduled to take place at Stennis Space Center in late 1998.
October 7, 1998	B.F. Goodrich completed the last major testing of the metallic panels for the X-33 thermal protection system at Marshall Space Flight Center.
October 14, 1998	NASA announced the reorganization of NASA's Code R—the Office of Aeronautics and Space Transportation Technology—under Associate Administrator Spence M. Armstrong, to the Office of Aero-Space Technology. In the NASA press release, it was reported that Armstrong stated that "Goldin wanted me to personally be an advocate for the Reusable Launch Vehicle programs to effect a cheaper means of access to space." The press release did not mention Gary Payton's changed role within Code R or on the X-33 program.
October 14, 1998	Boeing presented its estimate to complete engine delivery. Boeing's plan transferred $36 million from the VentureStar RLV to the half-scale X-33 by eliminating the fabrication, assembly, and testing of the RLV power pack. By adding a second engine test stand in Phase III (the program is presently in Phase II), Boeing developed a schedule that would support a first flight of the VentureStar within six months of the Skunk Works schedule. In addition, Boeing declined additional investment in the project. The $36 million transferred from the VentureStar to the X-33 was the same amount as the additional X-33 costs caused by Boeing's delay in delivering the aerospike engine.

Table 2–96. Reusable Launch Vehicle Chronology[a] *(Continued)*

Date	Event
October 21, 1998	The first two upper thermal protection system panels arrived at the hangar from B.F. Goodrich's Riverside plant. They were to be test fitted on the forward-most position of the liquid oxygen tank. Repair patches for liquid hydrogen tank #1 had been completed and shipped, while work continued on the second tank.
October 23, 1998	NASA announced that it and Lockheed Martin would hold a media teleconference on Tuesday, October 27, with program officials Gary Payton, NASA Deputy Associate Administrator for Space Transportation Technology, NASA Headquarters; Gene Austin, NASA X-33 Program Manager; Jerry Rising, Lockheed Martin Skunk Works Vice President for the X-33 and VentureStar; and Cleon Lacefield, Lockheed Martin Skunk Works X-33 Program Manager. A similar teleconference took place the previous October to update the media on the status of the program following the CDR. This teleconference was expected to announce a six-month delay in the X-33 flight tests.
October 27, 1998	In a joint NASA and Lockheed Martin media teleconference, Jerry Rising announced that the first flight of the X-33 would be delayed six months until December 1999 because of late delivery of the aerospike engine in September 1999. This delay in engine delivery would cost an additional $36 million. Lockheed Martin expected Rocketdyne to absorb the additional cost. Lockheed Martin had cut all overtime on the program and planned to cut project personnel to reduce escalating costs.
October 28, 1998	The two leeward #1 composite panels were delivered to the hangar for a fit check on the vehicle. The two leeward #2 panels were to be shipped on November 1 for a fit check. Once the panel fit checks were made, all composite panels would be shipped back to B.F. Goodrich's Riverside plant for completion. Also, a successful cure cycle on liquid hydrogen tank #2 was accomplished October 24–25. As a result, all lobe skins were bonded on both tanks.
November 6, 1998	NASA released the Hawthorne Report, named after the Boston firm, Hawthorne, Krauss, and Associates, LLC.[b] The firm conducted a study titled "Analysis of Potential Alternatives to Reduce NASA's Cost of Human Access to Space." NASA intended to use the Hawthorne Report and the Space Transportation Architecture Study currently under way as guides for planning future space launchers. The Hawthorne report strongly supported the economics of commercial RLVs over continued use of the Space Shuttle. Hawthorne also urged NASA to exercise caution in setting up loan guarantees to support development of commercial RLVs.

Table 2–96. Reusable Launch Vehicle Chronology[a] *(Continued)*

Date	Event
November 11, 1998	The X-33's electronics achieved an important milestone when Sanders shipped two Vehicle Health Monitoring computers to the Skunk Works. Also, the Skunk Works identified a potential winner of the contract to transport the X-33 over land.
November 13, 1998	A test of the aerospike engine power pack took place at 100 percent power over a period of 30 seconds during the week ending November 13. A 250-second test was planned for the following week.
November 18, 1998	Work began on the ballast bulkhead assembly. Faced with a continually slipping schedule at the Sunnyvale plant, subcontractor Alliant and the Lockheed Martin Skunk Works formulated a plan to speed up work. Shift schedules were changed to double manpower.
November 20, 1998	The announcement was made that NASA and Lockheed Martin had terminated the LASRE. The LASRE sought to obtain data on the aerospike engine intended for use on the X-33 and VentureStar by mounting half of a scale-model aerospike engine on the back of an SR-71 aircraft and studying the effects of gas flow. The modified SR-71 carried out seven LASRE test flights. Those flights, however, tested only cold flow gas conditions; all hot flow experiments were now cancelled. Two flights collected aerodynamic data on the combination of the aerospike engine with the SR-71 aircraft. In two other flights, gaseous helium and liquid nitrogen were cycled through the test rig to test its plumbing and, in three more flights, liquid oxygen flowed through the system. The two hot-fire test flights planned to validate computer models of aerospike performance in flight were now cancelled. The LASRE had been repeatedly delayed by hardware and other problems. Cancellation of the LASRE allowed any remaining funds to be used by the Skunk Works to cover X-33 cost overruns.
November 24, 1998	In its December 2, 1998, issue, Aerospace Daily reported that on November 24, 1998, Boeing's Rocketdyne Division completed the first four tests of its XRS-2200 linear aerospike engine at Stennis Space Center. In these tests, the engine's turbomachinery and gas generator were run at full power and then throttled back to 57 percent power.
December 1998	Construction of the X-33 Flight Operations Center was completed a little more than 12 months after groundbreaking. The center was located on the eastern portion of Edwards Air Force Base.

Table 2–96. Reusable Launch Vehicle Chronology[a] (Continued)

Date	Event
December 2, 1998	Aerospace Daily reported that NASA's Office of Inspector General, in an audit titled "X-33 Funding Issues" (IG-99-001), found that Marshall Space Flight Center allowed $56 million in year-end obligations for the X-33 to go unrecorded in FYs 1996 and 1997, thereby giving Congress an inaccurate picture of the program's status at the end of those two years. The Inspector General reported that Marshall contract officers had established an arrangement with Lockheed Martin to delay billing for completed X-33 work until the following fiscal year. In FY 1996, that amounted to $22 million, and in FY 1997, to $34 million. The Inspector General maintained that obligations "should be recorded not later than NASA's acceptance of the completed milestone work" and recommended that NASA adjust its financial records to reveal the X-33 program's financial status "fully and accurately," and that NASA review the funding and payment practices used on the X-33 program to ensure that they met the requirements of the Antideficiency Act and internal controls.
December 4, 1998	Senior NASA staff, Boeing representatives, and X-33 project personnel from Boeing, Rocketdyne, and Lockheed Martin attended a meeting at Lockheed Martin's corporate headquarters in Bethesda, Maryland, to discuss development of the X-33 aerospike engine. At the meeting, Boeing proposed to downsize the ground portion of the propulsion demonstration program to use the resulting savings to fund X-33 engine cost overruns. Three teams were formed to evaluate Boeing's proposal and to assess opportunities that NASA Centers might have to mitigate the impact on technology development. The results of these independent team assessments were to be reviewed in mid-January.
December 16, 1998	Construction of the X-33 continued. Both liquid hydrogen tanks completed cures. Two gaseous oxygen tanks and two methane tanks belonging to the auxiliary propellant system were installed on the liquid oxygen tank. The thrust structure was nearly complete. Some clearance issues had emerged during installation of the nose gear support structure. Power pack assembly No. 2 was completed and sent to Stennis Space Center for testing, while power pack assembly No. 1 was still having problems. Construction of the X-33 launch site continued. The four vehicle hold-down posts were installed onto the rotating launch mount. The diesel generator for the site's electrical supply was run for the first time. The Vehicle Positioning System was unpacked and set up for testing. Sanders completed delivery of the Operations Control Center hardware. The X-33 launch site was now complete.

Table 2–96. Reusable Launch Vehicle Chronology[a] *(Continued)*

Date	Event
December 18, 1998	NASA exercised an option with Orbital Sciences for 25 additional test flights during a 12-month period beginning immediately after completion of the initial contract. The option was valued at more than $10 million, with government organizations performing an additional $4.7 million in work.
March 2001	The X-33 and X-34 programs were cancelled.

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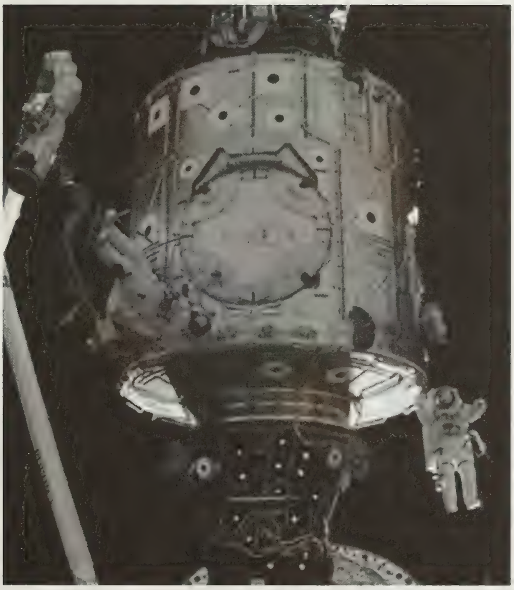
[a] Material in this table relating to the X-33 for the years 1996–1998 is drawn largely from Andrew Butrica, "Key X-33 Events," *http://www.hq.nasa.gov/office/pao/History/x-33/1998.htm.* (accessed March 15, 2005).

[b] Hawthorne, Krauss & Associates, LLC, "Analysis of Potential Alternatives to Reduce NASA's Cost of Human Access to Space," September 30, 1998, ftp://ftp.hq.nasa.gov/pub/pao/reports/1998/Hawrep.pdf (accessed May 18, 2005).



CHAPTER THREE

HUMAN SPACEFLIGHT

CHAPTER THREE

HUMAN SPACEFLIGHT

Introduction

NASA's human spaceflight undertakings seek to bring the frontier of space fully within the sphere of human activity, bringing people and machines together to overcome challenges of distance, time, and environment.[1] This chapter discusses NASA's human spaceflight activities during the decade from 1989 through 1998, focusing on Space Shuttle missions and the Space Station. It reviews the prior decade's activities; presents an overview of events during the 1989–1998 decade; summarizes the management and budget for human spaceflight at NASA; provides detailed information about each Space Shuttle mission; describes Space Shuttle payload accommodations; and discusses development of the Space Station.[2]

Most material in this chapter is based on primary NASA documents and Web-based NASA materials. These include pre- and post-launch mission operation reports, press kits and press releases, key personnel announcements, and various reports and plans issued by the Agency. Where applications activities are Shuttle-based, the Space Shuttle mission archives and mission chronologies have been consulted. The NASA projects have provided plentiful amounts of data. Most have comprehensive Web sites, and many also publish information booklets and fact sheets. Partner agencies, such as the European Space Agency (ESA), also publish printed and online material about their joint activities with NASA, as do the academic and private-sector institutions and organizations that are the homes of researchers and investigators. Most budget material comes from the annual budget estimates generated by the NASA Office of the Chief Financial Officer and from federal budget legislation. Other government agencies and organizations including the General Accounting Office, the Congressional Research Service, and the National Oceanic and Atmospheric Administration also issue reports and documents used as reference material. Measurements are presented in the unit used in the original reference (metric or English); conversions are in parentheses.

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[1] NASA Policy Directive (NPD) 1000.1, *NASA Strategic Plan* (Washington, DC: National Aeronautics and Space Administration, 1998), p. 26.

[2] Details of Spacelab missions are included in chapter 2, Earth Science and Applications, of Volume 8 of the *NASA Historical Data Book, 1989–1998.*

The Last Decade Reviewed (1979–1988)

The decade from 1979 through 1988 saw the inauguration of Space Shuttle flights in 1981, opening a new era of human spaceflight that had been on hold since the end of the Apollo era. Twenty-seven Shuttle flights took place during the decade; twenty-six were successful. The one unsuccessful flight, mission STS-51-L, set the tone for the remaining years of the decade, as the crew of the *Challenger* lost their lives in a catastrophic accident. Immediately after the accident, NASA began a far-reaching examination of the tragedy, using the findings of the independent Rogers Commission, appointed by President Ronald Reagan, and the NASA STS-51-L Data and Design Analysis Task Force to implement a set of recommendations that improved both the technical and management aspects of the human spaceflight program and increased the emphasis on safety. Two successful Shuttle missions at the end of the decade marked NASA's return to flight, as they demonstrated NASA's resilience and its determination to learn from the worst accident it ever experienced.

The 26 successful Shuttle flights deployed a variety of payloads from the government and commercial sectors and performed an array of scientific and engineering experiments. Four on-board Spacelab missions studied everything from plant life and monkey nutrition to x-ray emissions from clusters of galaxies.

Space Station development also began during the decade. In 1984, President Ronald Reagan directed NASA to develop and build a permanently manned Space Station and have it in place within a decade. NASA joined with partners in Europe (ESA), Canada, and Japan to begin developing Space Station *Freedom*. At the end of the decade, NASA and its partners had completed the Definition and Preliminary Design Phase and begun the Design and Development Phase.

Overview of Human Spaceflight (1989–1998)

During 1989–1998, NASA's human spaceflight activities focused on the Space Shuttle both as a launch vehicle and as a venue for a wide range of experiments. NASA also focused on developing the largest free-flying facility ever, the Space Station. NASA launched 66 Space Shuttle missions during the decade. These missions launched satellites into space, conducted on-board experiments, and performed rendezvous and docking exercises as part of the Shuttle-*Mir* program, the first phase of the International Space Station program. Spacelab activities on board the Shuttle and *Mir* began in 1983 with STS-9 and concluded in 1998. This series of international missions paved the way for research aboard the Space Station. Over its 17-year flight history, 22 Spacelab missions hosted payloads in practically every research discipline in which NASA engaged except those associated exclusively with planetary exploration. Between 1989 and 1998, 18 Spacelab missions flew.

This chapter summarizes each Shuttle mission and describes the on-board payloads and experiments on each mission. Descriptions of launched spacecraft, as well as descriptions of payloads launched and retrieved by the Shuttle, can be found in the chapters relating to space science, applications, and communications. Table 3–51 provides a summary list of all Space Shuttle missions with their major payloads.

Space Station development was undoubtedly the most ambitious NASA human spaceflight activity during the decade. NASA initiated the International Space Station program, but the orbiting laboratory was designed as an international undertaking, with participation by ESA, Japan, Canada, Italy (both as ESA member and NASA contractor), Russia from 1993, and Brazil (to a limited extent). The project, initially named Space Station *Freedom* by President Ronald Reagan in 1988, was the object of regular debate over its cost and scientific merit and, at the start of the decade, had already undergone redesigns in an effort to reduce its cost.

In 1993, President William J. Clinton, concerned by the cost and determined to reduce the federal deficit, ordered NASA to redesign the Station to make it simpler, smaller, and cheaper. The chosen redesign, with fewer capabilities, was first called Space Station *Alpha*. It became the International Space Station (ISS) with development spread over three phases. The ISS had Russia as a full-fledged partner contributing the first element, the service module, and a number of other essential components. The program also streamlined construction and management in the United States by assigning Johnson Space Center to be the host Center and eliminating *Freedom*'s complex work package structure with its independent contractors.[3] Instead, it consolidated all work under a single prime contractor, Boeing, with responsibility for the entire project.

The first phase of ISS development, lasting through 1998, consisted primarily of the Shuttle-*Mir* program in which U.S. astronauts spent months at a time aboard the orbiting Russian *Mir* space station. The purpose of these missions was to accustom American astronauts to living in space for long periods, provide additional experience with spacecraft rendezvous and docking, and develop good working relations between U.S. and Russian crew members. The second and third phases, which began at the end of 1998, comprised ISS assembly. Phase II consisted of initial on-orbit construction. It began with launch of the first ISS elements in 1998, providing initial living quarters and life support systems, and ending with launch of a three-person crew that marked the beginning of permanent ISS habitation. Phase III, the "assembly complete" phase, was to consist of remaining assembly, including the addition of laboratory modules, attaching a robotic arm, and crews of up to seven members.[4]

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[3] NASA used the term "host Center" to describe the role of Johnson Space Center in the Space Station program and the term "lead Center" to describe its role in the Space Shuttle program.

The program experienced continuous problems and delays due both to financial problems with its Russian partner and to an overly ambitious schedule and significant cost overruns by the U.S. prime contractor. Russian contributions were intended to be "enhancing" rather than "enabling," but it was clear that the country's contributions were needed for assembly to proceed. Russia lacked the funds to pay their prime contractor, causing years of schedule delays for both individual elements and project completion.

Although occurring years later than originally planned, on-orbit assembly began before the end of the decade, with successful deployment of the first two elements in 1998. The Russian Zarya (paid for with U.S. funds) was launched in November from Russia; the first U.S. module, Unity, was successfully delivered by Shuttle and joined with Zarya early in December 1998.

Management of Human Spaceflight Programs

The management and organizational structure of both the Space Shuttle and Space Station programs changed frequently as the technical nature of the programs evolved and as NASA sought to make the programs and their management more efficient. Some of these changes merely consolidated existing organizations or gave them new names that better reflected their functions; others eliminated divisions or offices; other changes established new divisions or offices. The sections that follow describe many of these changes.

NASA used a letter designation (called a "code") as an easy way to refer to its top-level organizations, or "offices." When an office was first formed, there was usually a connection between the assigned letter and the office's function (for instance, Code M was Manned Spaceflight), but in general, any connection became less likely over time as offices were created and eliminated, and many new letter designations were chosen merely because the letter was available. In the area of human spaceflight, the following letter designations were used during the decade from 1989 to 1998 and are mentioned in this chapter:

- Office of Space Flight–Code M
- Office of Space Station–Code S

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[4] "Assembling a World-Class Orbiting Laboratory, Phases Two and Three," *http://spaceflight.nasa.gov/station/reference/fel/phases2_3.html* (accessed November 21, 2005). Also "ISS Program Phases," Boeing, *http://www.boeing.com/defense-space/space/spacestation/overview/program_phases.html* (accessed November 21, 2005).

- Office of Space Systems Development–Code D
- Office of Life and Microgravity Sciences and Applications–Code U

For general information about NASA's organizational structure, see chapter 1 of this volume and the chapter titled Facilities and Installations in Volume VIII of the *NASA Historical Data Book* for a description of each NASA Center.

Management of the Space Shuttle Program

The Headquarters Office of Space Flight (Code M) managed the Space Shuttle program. Chapter 2 describes the various reorganizations as well as personnel assignments and transfers within that organization. Briefly, in 1989, the Office of Space Flight organized into three major divisions: Institutions, Flight Systems, and the National Space Transportation System (NSTS) program. NSTS was soon renamed the Space Shuttle program. In December 1989, the Office of Space Flight added management of the Space Station program to its other responsibilities, moving it from an independent organization.[5] In 1991, several organizations related to development of new space transportation systems, including Space Station development, moved from the Office of Space Flight to a new organization, the Office of Space Systems Development (Code D). The operational aspects of the Shuttle program remained in Code M as did Spacelab and Space Station *Freedom* operations and utilization. In October 1993, the Office of Space Flight again assumed responsibility for the entire Space Station program.

The Office of Space Flight reorganized in October 1995 into four major offices: the Business Management Office, the Space Station Program Office, the Space Shuttle Program Director, and the Advanced Projects Office. A major Agency restructuring in October 1996 merged the Office of Space Communications into the Office of Space Flight. In July 1998, the final reorganization of the decade took place as the Office of Space Flight organized into four functional offices: Operations, Enterprise Development, Business Management, and Development.

Although overall management of the Space Shuttle program resided at NASA Headquarters, several NASA Centers had particular responsibilities relating to the program. Johnson Space Center in Houston, Texas, was designated the Space Shuttle Program Lead Center and managed development and operation of the Space Shuttle. Johnson Space Center was responsible for flight crew operations; mission operations; extravehicular activity; mission support; program safety and mission assurance; and design and development of the orbiter and crew-related government-furnished equipment. The Johnson Customer and Flight Integration office managed integration of the customer's payload into the Shuttle.

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[5] NASA Management Instruction 1102.5E, "Roles and Responsibilities–Associate Administrator for Space Flight," Effective December 29, 1989 (NASA History Office Folder 14829).

The Space Shuttle program manager at Johnson had full responsibility and authority to operate and conduct the program. Among the elements within this person's area of authority and responsibility were: overall program requirements and performance; total program control, including budget, schedule, and program content; approval of critical hardware waivers and deviations; budget authorization adjustments that exceeded a predetermined level; informing the Johnson Space Center director of program content and status; and integration of payloads with the orbiter.

Representatives of the Space Shuttle program elements, projects, and directorates supporting program activities were also part of the management team. They were located at various NASA Centers.

Kennedy Space Center in Cape Canaveral, Florida, was the launch site and primary landing site for the Shuttle. The Center was responsible for design, development, and operation of the launch and landing site facilities and support equipment; ground turnaround testing and maintenance of the orbiter; payload processing and installation into the orbiter; retrieval and disassembly of the solid rocket boosters; and conduct of all prelaunch and launch countdown activities required for each Space Shuttle mission. The launch integration manager at Kennedy was responsible for final vehicle preparation and return of the orbiter for processing for its next flight; managing the Certification of Flight Readiness process; presenting and scheduling of the Flight Readiness Review; the final launch decision process including final authority to commit to launch; and chairing the Mission Management Team before launch.

Marshall Space Flight Center in Huntsville, Alabama, through its Space Shuttle Projects Office, managed design, development, and integration of the solid rocket boosters, external tanks, and the Space Shuttle main engines.

Goddard Space Flight Center in Greenbelt, Maryland, managed the worldwide NASA communications network, including the Tracking Data and Relay Satellite System used to maintain communications with the Shuttle. In addition, Goddard oversaw the Get Away Special (GAS) program and several other small payload carrier programs. Stennis Space Center in Mississippi was responsible for testing the Shuttle's main engines.

Figure 3–1 shows the Space Shuttle program organization. Figure 3–2 is an expanded diagram showing the project elements assigned to Johnson Space Center, Marshall Space Flight Center, and Kennedy Space Center that together support the manager of the Space Shuttle program at Johnson Space Center in carrying out the program's responsibilities.

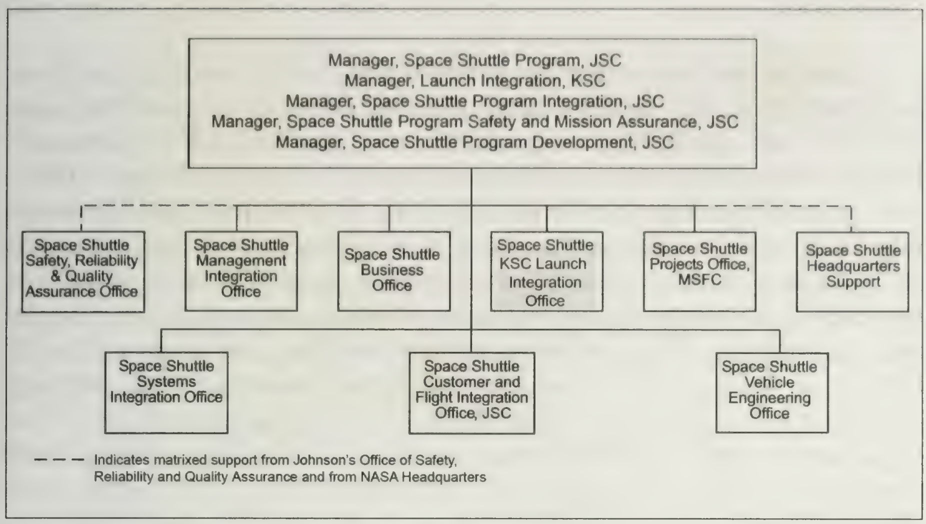
Manager, Space Shuttle Program, JSC
Manager, Launch Integration, KSC
Manager, Space Shuttle Program Integration, JSC
Manager, Space Shuttle Program Safety and Mission Assurance, JSC
Manager, Space Shuttle Program Development, JSC
Space Shuttle Safety, Reliability & Quality Assurance Office
Space Shuttle Management Integration Office
Space Shuttle Business Office
Space Shuttle KSC Launch Integration Office
Space Shuttle Projects Office, MSFC
Space Shuttle Headquarters Support
Space Shuttle Systems Integration Office
Space Shuttle Customer and Flight Integration Office, JSC
Space Shuttle Vehicle Engineering Office
– – – Indicates matrixed support from Johnson's Office of Safety, Reliability and Quality Assurance and from NASA Headquarters

Figure 3–1. Space Shuttle Program Organization, December 1997.[6]

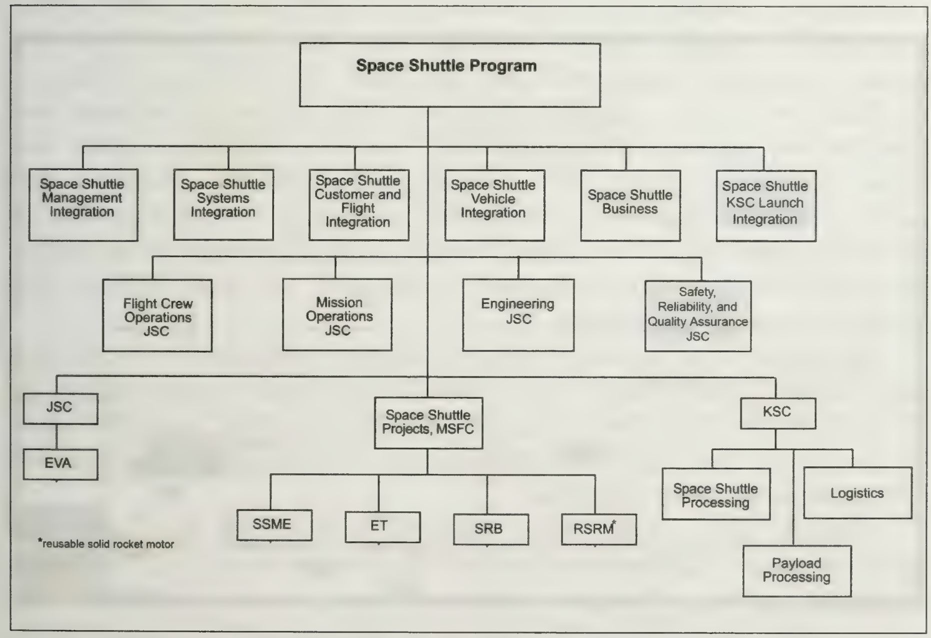
Space Shuttle Program
Space Shuttle Management Integration
Space Shuttle Systems Integration
Space Shuttle Customer and Flight Integration
Space Shuttle Vehicle Integration
Space Shuttle Business
Space Shuttle KSC Launch Integration
Flight Crew Operations JSC
Mission Operations JSC
Engineering JSC
Safety, Reliability, and Quality Assurance JSC
JSC
EVA
Space Shuttle Projects, MSFC
KSC
Space Shuttle Processing
Logistics
Payload Processing
SSME
ET
SRB
RSRM*
*reusable solid rocket motor

Figure 3–2. Space Shuttle Program Elements and Projects, December 1997.[7]

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[6] Derived from "Space Shuttle Program Description and Requirements Baseline; Program Definition and Requirements," NSTS 07700 Volume I, Rev. G, December 17, 1997, pp. 3–17, *http://pbma.nasa.gov/docs/public/pbma/bestpractices/bp_jsc_44.pdf* (accessed June 28,2005).

[7] Derived from "Space Shuttle Program Description and Requirements Baseline; Program Definition and Requirements," NSTS 07700 Volume I, Rev. G, December 17, 1997, pp. 3–18, *http://pbma.nasa.gov/docs/public/pbma/bestpractices/bp_jsc_44.pdf* (accessed June 28, 2005).

Spacelab Management

Spacelab missions on the Space Shuttle and on *Mir* were the precursor to ISS activities. All major preparatory events leading to a Spacelab mission generally fell under the responsibility of four NASA departments: Headquarters, the Mission Management Office, the Mission Science Office, and payload element developers. NASA Headquarters was generally responsible for establishing mission objectives, sending out Announcements of Opportunity, and reviewing the experiment proposals. In the middle of the decade, the Life Sciences Flight program and the Space Shuttle/ Spacelab Mission Management and Integration program in the Office of Life and Microgravity Sciences and Applications selected, defined, developed, and conducted in-space medical and biological research. These organizations also performed the mission planning, integration, and execution of all NASA-Spacelab, NASA-*Mir* Research Program, and attached Space Shuttle payloads.

The Spacelab management team was responsible for overseeing all aspects of hardware integration and coordination of all mission-related support activities. The mission manager served as the interface between the payload element developers' management and the Space Shuttle Program Office to maximize the mission objectives consistent with science requirements and Spacelab and orbiter system constraints. The Mission Science Office was responsible for organizing and coordinating all activities associated with payload specialist selection and experiment development. The payload element developers, reporting to the mission manager, were responsible for the design, fabrication, test, and formal turnover of experiment hardware, software, and experiment operating procedures.

Other offices that provided oversight management functions for a Spacelab mission included the Johnson Space Center Space Shuttle Program Office, the Marshall Space Flight Center Spacelab Management Office, Kennedy Space Center Launch Site Support Management, and Goddard Space Flight Center Communications and Data Support.

Marshall Space Flight Center was NASA's lead Spacelab Center and provided project management oversight for Spacelab hardware. The Center developed selected Spacelab hardware and provided technical and programmatic monitoring of the international Spacelab development effort. Marshall was also responsible for managing many Spacelab missions, including developing mission plans; integrating payloads; training payload crews; and controlling payload operations. The Payload Operations Control Center, which controlled Spacelab, was located at Marshall.

Management of the Space Station Program

The Space Station program underwent numerous organizational and management changes between 1989 and 1998 as it changed from Space Station *Freedom* to the ISS, brought Russia on board as a full-fledged partner, moved its center of operations from Reston, Virginia, in the Washington, DC, area to Johnson Space Center in Texas, and scaled down the size and complexity of the program. The following sections address the program structure and management. Note that the phases used below represent changes in management or management structure and are used to organize the discussion. They do not correspond with the NASA's three formal phases of Space Station development discussed later in this chapter.

Phase I: 1989–1992

Beginning in 1984, the Office of Space Station (Code S), an independent program office, managed the Space Station Freedom program (see Figure 3–3). Management was spread among three levels.

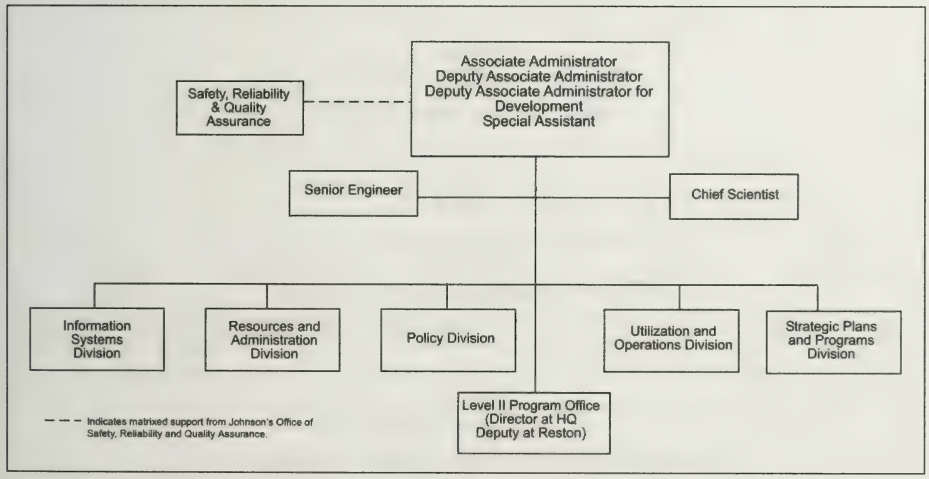
Associate Administrator
Deputy Associate Administrator
Deputy Associate Administrator for Development
Special Assistant
Safety, Reliability & Quality Assurance
Senior Engineer
Chief Scientist
Information Systems Division
Resources and Administration Division
Policy Division
Utilization and Operations Division
Strategic Plans and Programs Division
Level II Program Office (Director at HQ Deputy at Reston)
– – – Indicates matrixed support from Johnson's Office of Safety, Reliability and Quality Assurance.

Figure 3–3. Headquarters Office of Space Station (Code S), December 1988.[8]

Level I comprised the Office of the Associate Administrator for the Office of Space Station (Code S) at NASA Headquarters. The Associate Administrator was responsible for overall program management and strategic planning. Level I was responsible for defining and controlling program requirements, schedule, milestones, and resources. The Level I divisions were Information Systems, Resources and Administration, Policy, Utilization and Operations, and Strategic Plans and Programs.

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[8] "Roles and Responsibilities–Associate Administrator for Space Station," NASA Management Instruction 1102.12A, Ch. 1, Attachment A, December 16, 1988.

Level II consisted of the Space Station Program Office in Reston, Virginia. It was responsible for development of the Space Station, the operational capability of flight and ground systems, and the control of internal and external interfaces. The director of the Space Station program headed this office and was responsible for day-to-day management. Four offices—Safety/Product Assurance, Program Support, Program Integration, and Program Requirements and Assessment—and five groups—Program Control, Program Information Systems Services, Program Utilization and Operations, Program Systems Engineering and Integration, and International Programs—comprised Level II. NASA's accounting and procurement offices provided additional support.

Level III comprised the four work package Centers at the NASA Field Centers and their contractors. They were responsible for design, development, testing, and evaluation; operation of hardware and software systems; and element, evolution, and engineering support. A Space Station Project Office was located at each work package Center. The project manager of each Level III office reported to the director of the Space Station program at Level II. Figure 3–4 shows the three-tiered structure as it existed in April 1989.

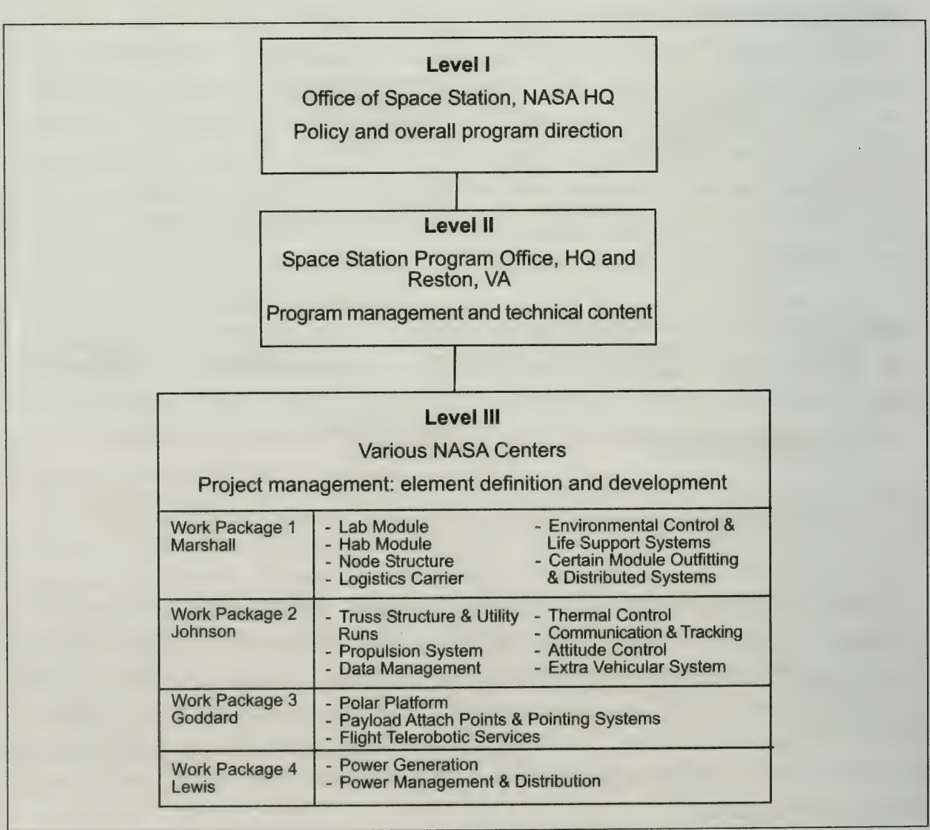
Level I
Office of Space Station, NASA HQ
Policy and overall program direction
Level II
Space Station Program Office, HQ and Reston, VA
Program management and technical content
Level III
Various NASA Centers
Project management: element definition and development
Work Package 1 Marshall
- Lab Module
- Hab Module
- Node Structure
- Logistics Carrier
- Environmental Control & Life Support Systems
- Certain Module Outfitting & Distributed Systems
Work Package 2 Johnson
- Truss Structure & Utility Runs
- Propulsion System
- Data Management
- Thermal Control
- Communication & Tracking
- Attitude Control
- Extra Vehicular System
Work Package 3 Goddard
- Polar Platform
- Payload Attach Points & Pointing Systems
- Flight Telerobotic Services
Work Package 4 Lewis
- Power Generation
- Power Management & Distribution

Figure 3–4. Tiered Space Station Organizational Structure, April 1989.[9]

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[9] *Space Station Freedom Media Handbook* (Washington, DC: Technical & Administrative Services Corporation, 1989), p. 10.

Level III Field Centers

Marshall Space Flight Center

Marshall Space Flight Center in Huntsville, Alabama, was the Work Package 1 Center. Work Package 1 included the design and manufacture of the astronauts' living quarters (Habitation Module); the U.S. Laboratory Module and logistics elements for resupply and storage; node structures connecting the modules; the Environmental Control and Life Support System; and the Internal Thermal Control and Audio/Video Systems in the pressurized modules.

Marshall also provided technical direction for the design and development of the engine elements of the propulsion system and was responsible for operations capability development associated with the Station's payload operations and planning. Boeing Aerospace was the Work Package 1 prime contractor. Figure 3–5 shows the Marshall Space Station organization.

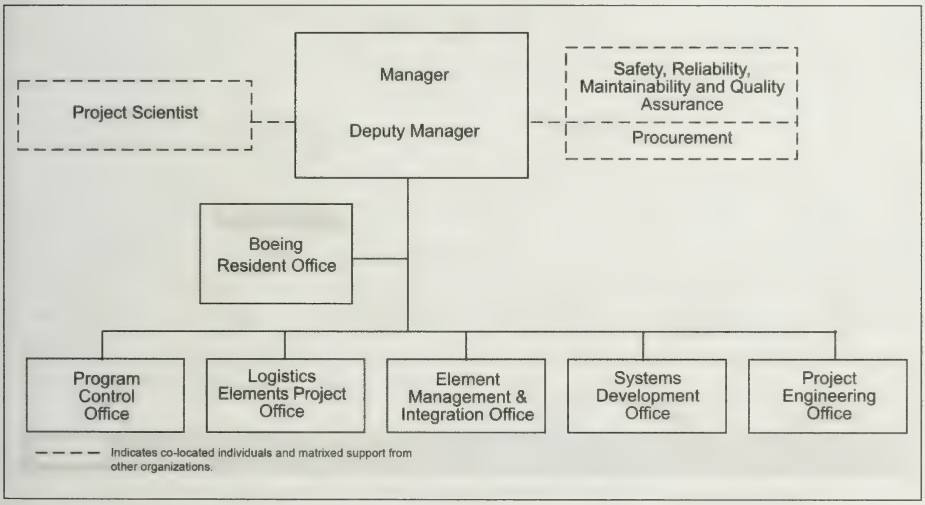
Project Scientist
Manager
Deputy Manager
Safety, Reliability, Maintainability and Quality Assurance
Procurement
Boeing Resident Office
Program Control Office
Logistics Elements Project Office
Element Management & Integration Office
Systems Development Office
Project Engineering Office
– – – – Indicates co-located individuals and matrixed support from other organizations.

Figure 3–5. Marshall Space Flight Center Space Station Organization, April 1989.[10]

Johnson Space Center

Johnson Space Center, near Houston, Texas, was responsible for managing the design, development, test, and engineering of Work Package 2 flight elements and systems. These included the integrated truss assembly, propulsion assembly, mobile transporter system, outfitting of the resource node structures provided by Work Package 1, extravehicular system, and the external thermal control system. The extravehicular activity system included the extravehicular mobility unit (the spacesuit), associated life support, and other support equipment. Johnson was also responsible for the attachment systems for docking the Space Shuttle with the Space Station as well as the attachment systems needed for logistics supply modules; the guidance, navigation, and control system; the communications and tracking system; the data management system; and the airlocks. The Center's prime contractor was McDonnell Douglas Astronautics.

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[10] *Space Station Freedom Media Handbook,* 1989, p. 33.

Johnson provided technical direction for the design and development of all human space subsystems. These included crew quarters restraints and mobility aids; health care; operational and personal equipment; portable emergency provisions; workstations; galley and food management; personal hygiene; lighting; wardroom; stowage; and housekeeping/trash management. It was also responsible for providing a portion of the Canadian Space Agency's Mobile Servicing System training for the Space Station crew and Johnson ground support personnel. Figure 3–6 shows Johnson's Space Station organization.

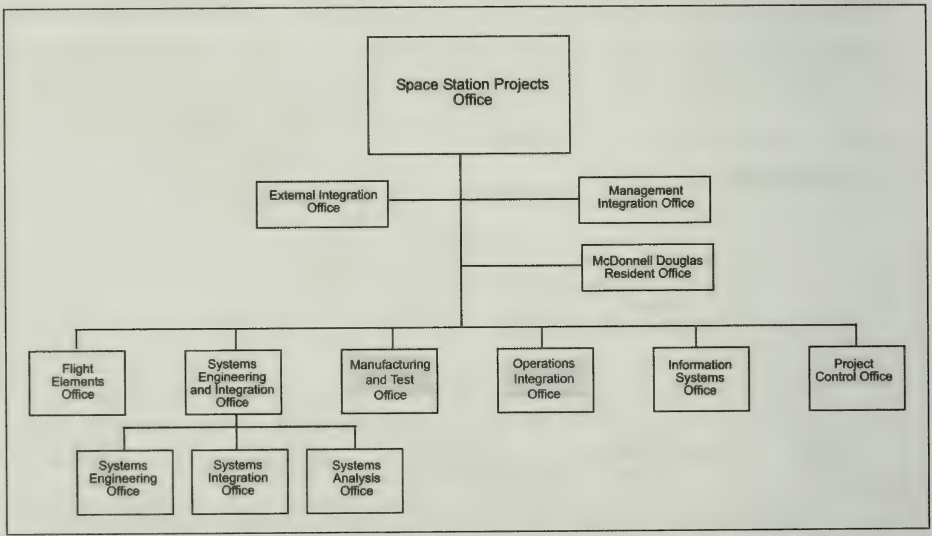
Space Station Projects Office
External Integration Office
Management Integration Office
McDonnell Douglas Resident Office
Flight Elements Office
Systems Engineering and Integration Office
Manufacturing and Test Office
Operations Integration Office
Information Systems Office
Project Control Office
Systems Engineering Office
Systems Integration Office
Systems Analysis Office

Figure 3–6. Johnson Space Center Space Station Organization, April 1989.[11]

Goddard Space Flight Center

Goddard Space Center in Greenbelt, Maryland, was responsible for managing the design, development, test, and engineering of Work Package 3 flight elements and systems. Goddard and its prime contractor, the Astro-Space Division of General Electric Company, were to manufacture the servicing facility, the flight telerobotic servicer, the accommodations for attached payloads, and the U.S. uncrewed free-flyer platforms. However, as part of the 1991 reorganization, Work Package 3 and Goddard's participation in the Space Station Freedom program were terminated. Figure 3–7 shows Goddard's Space Station organization as of 1989.

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[11] *Space Station Freedom Media Handbook*, 1989, p. 50.

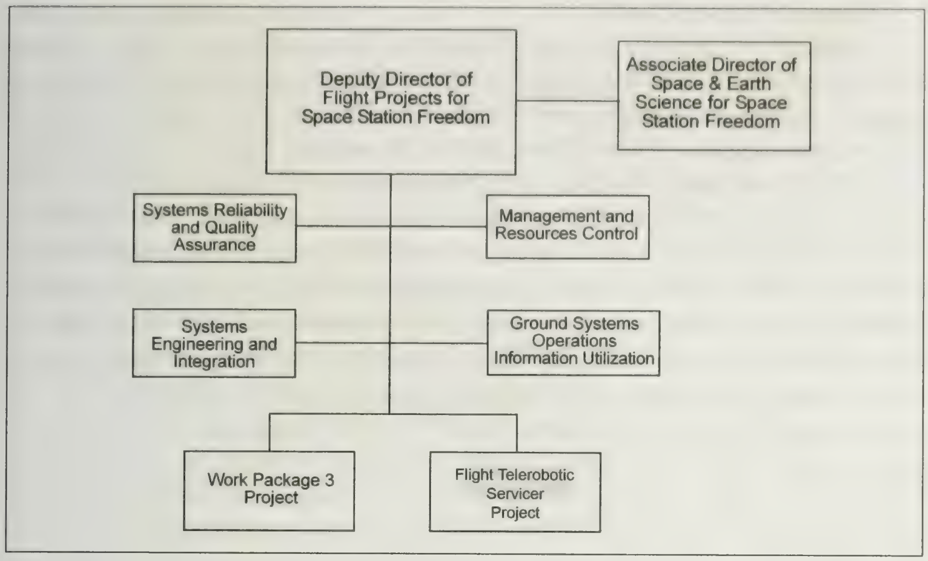
Deputy Director of Flight Projects for Space Station Freedom
Associate Director of Space & Earth Science for Space Station Freedom
Systems Reliability and Quality Assurance
Management and Resources Control
Systems Engineering and Integration
Ground Systems Operations Information Utilization
Work Package 3 Project
Flight Telerobotic Servicer Project

Figure 3–7. Goddard Space Flight Center Space Station Organization, April 1989.[12]

Lewis Research Center

Lewis Research Center in Cleveland, Ohio, was responsible for the Work Package 4 portions of the Space Station, consisting of the design and development of the entire electric power system; photovoltaic power generation subsystem; energy storage subsystem; solar power module; and primary power distribution. The Power Systems Facility at Lewis provided the capability to develop, test, and evaluate prototype power systems hardware for the program. Figure 3–8 shows Lewis's Space Station organization.

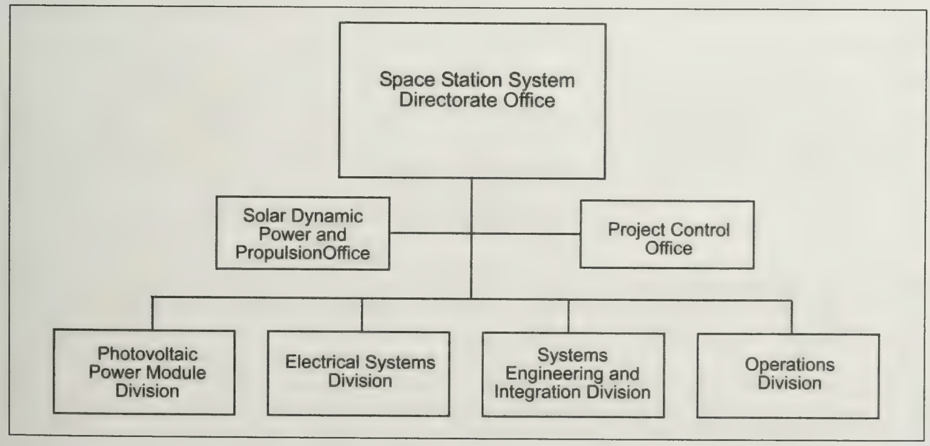
Space Station System Directorate Office
Solar Dynamic Power and PropulsionOffice
Project Control Office
Photovoltaic Power Module Division
Electrical Systems Division
Systems Engineering and Integration Division
Operations Division

Figure 3–8. Lewis Research Center Space Station Organization.[13]

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[12] *Space Station Freedom Media Handbook*, 1989, p. 54.
[13] *Space Station Freedom Media Handbook*, 1989, p. 70.

Kennedy Space Center

Although not a work package Center, the Kennedy Space Station Project Office was devoted to Space Station systems engineering and integration, ground support equipment management, operations and customer support, project control, and logistics systems. Because NASA was the Agency responsible for integrating both international and U.S. elements and systems with the Shuttle, Kennedy was the focal point for prelaunch and launch activities. The Center was responsible for launch sites; launch site common ground support equipment; facilities to support prelaunch and postlanding processing; payload processing and logistics; management and operations of integrated logistics systems; and the Space Station Processing Facility. Technicians from the Space Station partners would provide technical and hands-on support for the integration of the international elements at Kennedy. The Kennedy Space Station *Freedom* test teams would provide launch site final acceptance testing to verify major interfaces, provide confidence tests of critical systems, and verify end-to-end operations between the flight elements and ground control Centers. Figure 3–9 shows Space Station project organization at Kennedy.[14]

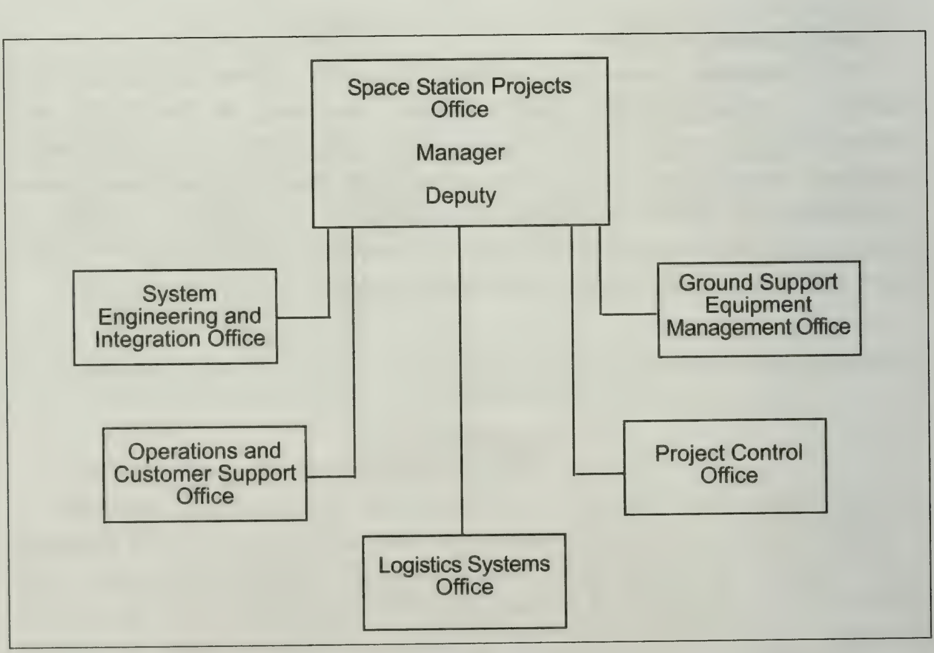
Space Station Projects Office
Manager
Deputy
System Engineering and Integration Office
Ground Support Equipment Management Office
Operations and Customer Support Office
Project Control Office
Logistics Systems Office

Figure 3–9. Kennedy Space Center Space Station Organization, April 1989.[15]

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[14] *Space Station Freedom Media Handbook* (Washington, DC: Technical & Administrative Services Corporation, 1992), pp. 9, 24–71.

[15] *Space Station Freedom Media Handbook*, 1989, p. 74.

Space Station Management

James B. Odom was Associate Administrator for the Office of Space Station at NASA Headquarters from March 1988 until his retirement on April 30, 1989. When Odom retired, Thomas L. Moser served briefly as acting Associate Administrator until he left NASA in mid-May 1989. On May 18, NASA acting Administrator Richard Truly named Dr. William B. Lenoir Associate Administrator for the Office of Space Station effective 1 June. On July 13, 1989, he was also appointed acting Associate Administrator for the Office of Space Flight, filling the position held by Truly, before he became NASA Administrator. Truly asked Lenoir to develop a plan to consolidate the Office of Space Flight and the Office of Space Station. Henry Hartsfield was assigned temporary duty to direct the Space Flight/Space Station Integration Office, replacing Robert Parker.[16]

In Reston, Virginia, E. Ray Tanner became Director of the Space Station Freedom Program Office on January 3, 1989.[17] On May 18, 1989, Truly named Richard Kohrs Director of Space Station Freedom at NASA Headquarters, and Tanner Deputy Director of Space Station Freedom Program and Operations in Reston, Virginia. James Sisson was named as acting Deputy Director for the Space Station Freedom Program Office, moving from his position as Deputy Program Manager for the Space Station Freedom Program Office.[18]

At the beginning of October 1989, Sisson, moved from acting Deputy Director, Program and Operations of the Space Station Freedom Program Office, to the position of Deputy Manager, Space Station Freedom Program and Operations. Robert W. Moorehead became the new Deputy Director, Program and Operations, of the Space Station Freedom Program Office.[19]

In November 1989, Truly announced the consolidation of the Space Station Program and Space Shuttle Program into a combined organization named the Office of Space Flight (Code M), effective December 1989.[20] (See Figure 2–3 in chapter 2 of this volume.) The combined organization made sense, NASA explained, because the Space Station would be launched using the Shuttle and assembled in-orbit. Having both activities under a single Associate Administrator would improve communications and decision making in several key areas, including the assembly sequence and Space Shuttle-Space Station interfaces. In addition, the astronauts who would assemble and operate the Station would more directly influence its design.[21]

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[16] The integration office had been established in 1987 to facilitate integration of the Space Station into the Space Transportation System.

[17] "Tanner Named Director Space Station Freedom Program," *NASA News* Release 88–175, December 29, 1988 (NASA History Office Folder 009610).

[18] "Space Station Program Leadership Selected by Truly," *NASA News* Release 89–77, May 19, 1989 (NASA History Office Folder 009610). Tanner retired from NASA on July 15, 1989.

[19] "Moorehead Named Space Station Freedom Program Deputy," *NASA News* Release 89–155, October 2, 1989 (NASA History Office Folder 009610).

[20] NASA Management Instruction 1102.5E, "Roles and Responsibilities–Associate Administrator for Space Flight," Effective December 29, 1989 (NASA History Office Folder 14829).

[21] Office of Space Flight, National Aeronautics and Space Administration, "Space Station Level II Management and Integration Status," June 1990, pp. 4–6 (NASA History Office Folder 009524).

Richard Kohrs headed the Space Station Freedom Program Office, one of the two major divisions in the Office of Space Flight. Richard A. Thorson, at Johnson Space Center, became Deputy Program Manager of Space Station Freedom Systems Integration Office. Level II Integration Offices were established at Marshall Space Flight Center and Johnson Space Center. James Sisson became Manager of the Element Integration Office at Marshall. Jesse F. Goree, Jr., became acting Manager of the Systems Integration Office at Johnson. Figure 3–10 shows the management structure of the Space Station Freedom Program Office as of May 1990. It shows the same tiered structure that had been in place since the program's inception. Level I provided overall program direction and policy. Level II provided day-to-day management and overall system engineering and integration. The Level III Field Center project offices directed the design and development of the hardware and software, which was performed by the contractor teams below them.

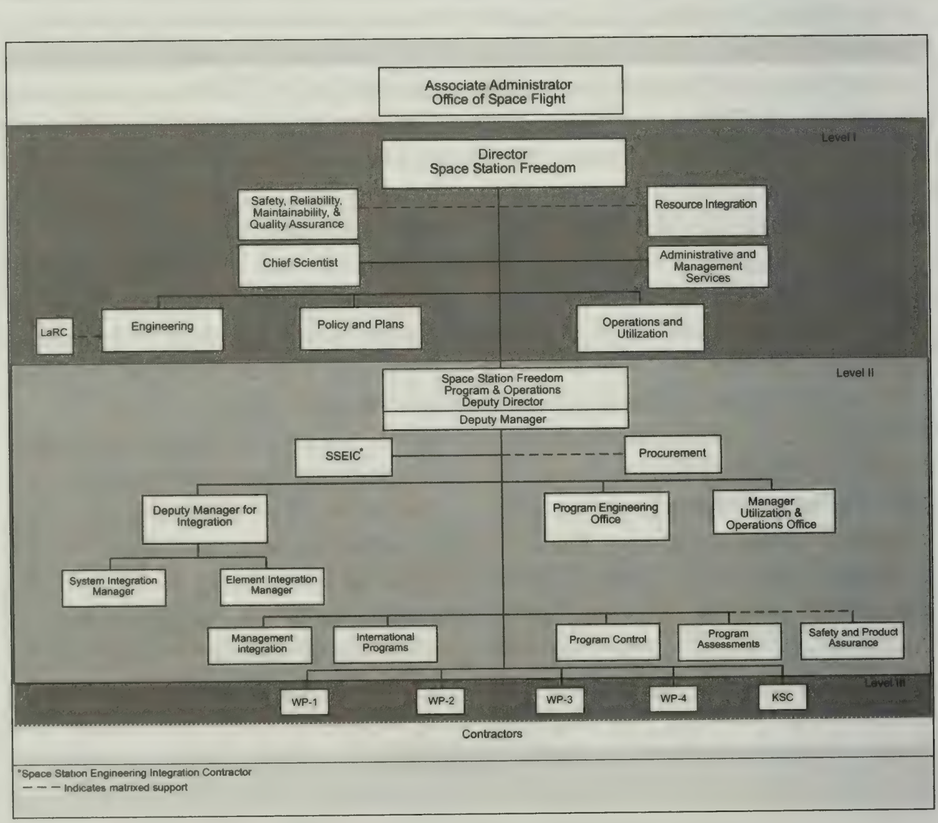
Associate Administrator
Office of Space Flight
Level I
Director
Space Station Freedom
Safety, Reliability, Maintainability, & Quality Assurance
Resource Integration
Chief Scientist
Administrative and Management Services
LaRC
Engineering
Policy and Plans
Operations and Utilization
Space Station Freedom Program & Operations Deputy Director
Deputy Manager
Level II
SSEIC*
Procurement
Deputy Manager for Integration
Program Engineering Office
Manager Utilization & Operations Office
System Integration Manager
Element Integration Manager
Management Integration
International Programs
Program Control
Program Assessments
Safety and Product Assurance
Level III
WP-1
WP-2
WP-3
WP-4
KSC
Contractors
*Space Station Engineering Integration Contractor
— — — Indicates matrixed support

Figure 3–10. Space Station Freedom Program Office, May 1990.[22]

In December 1990, the Advisory Committee on the Future of the U.S. Space Program, led by Norman Augustine, issued a report that, among its recommendations, advised separating operations from development and grouping the Space Station program with other development programs headed by a NASA Associate Administrator for spaceflight development. It also recommended locating "a strong and independent project office reporting to headquarters" near the NASA Center that had the most work for the project.[23] As a result, on September 13, 1991, Truly announced plans to create a new office to be named the Office of Space Systems Development (Code D). The new organization would have responsibility for Space Station *Freedom* development as well as other development programs (see Figure 3–11). The Office of Space Flight would retain responsibility for Space Station *Freedom*-Spacelab operations, the Space Shuttle program, and other areas of spaceflight operations.[24] On October 3, Truly named Arnold D. Aldrich Associate Administrator for the new organization, and Dr. C. Howard Robins, Jr., as Deputy. Richard Kohrs was named Deputy Associate Administrator for Space Station *Freedom.*

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[22] "Space Station Level II Management and Integration Status," Office of Space Flight, National Aeronautics and Space Administration, June 1990, (NASA History Office Folder 009524).

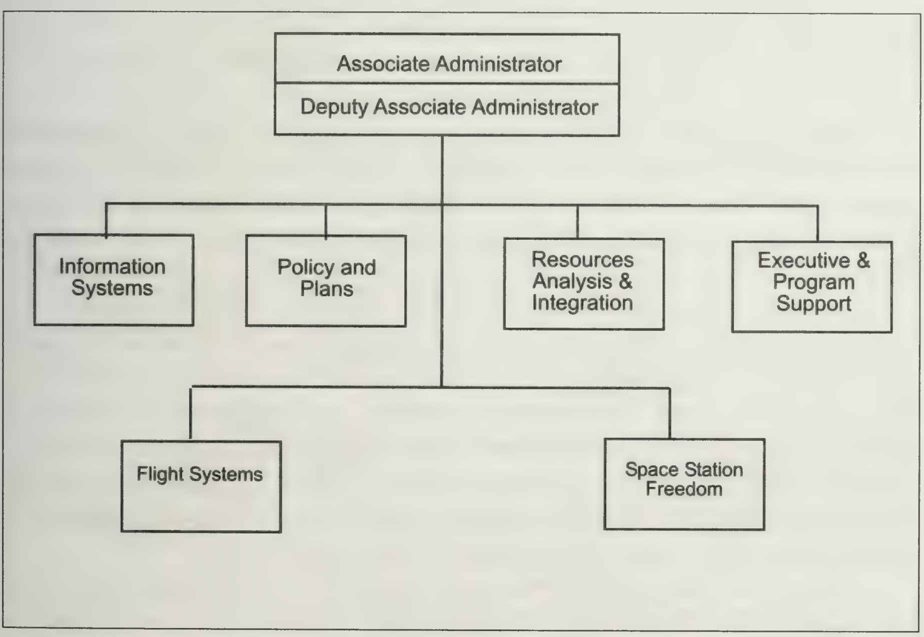
Associate Administrator
Deputy Associate Administrator
Information Systems
Policy and Plans
Resources Analysis & Integration
Executive & Program Support
Flight Systems
Space Station Freedom

Figure 3–11. Office of Space Systems Development (Code D).

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[23] Advisory Committee on the Future of the U.S. Space Program, "Report of the Advisory Committee on the Future of the U.S. Space Program, December 1990," *http://www.hq.nasa.gov/pao/History/augustine/racfup1.htm* (accessed March 15, 2005).

[24] "New Office of Space Flight Development Announced," *NASA News* Release 91–148, September 13, 1991 (NASA History Office Folder 009610).

Phase II: 1992–1994

On March 30, 1992, William Lenoir announced that he would be leaving his position as head of the Office of Space Flight and retiring from NASA in May. On April 28, the new NASA Administrator, Daniel S. Goldin, announced the appointment of Major General Jeremiah W. Pearson, III as Associate Administrator of the Office of Space Flight.

During 1992, Space Station *Freedom* continued to use a three-tiered management structure, although the program had moved from the Office of Space Flight (Code M) to the newly established Office of Space Systems Development (Code D). Responsibilities of the three levels remained essentially unchanged after the move, with the exception that there were now only three Work Package centers—Marshall Space Flight Center, Johnson Space Center, and Lewis Research Center.[25] Level I consisted of the Associate Administrator for the Office of Space Systems Development (Code D) at NASA Headquarters; Level II, the Deputy Director, Program and Operations in Reston, Virginia; and Level III, the NASA Field Centers' Space Station Freedom Project Offices (see Figure 3–12). The managers of these Level III project offices reported to the Deputy Director of the Space Station program on Level II.

Outside the Work Package structure, the Johnson Mission Operations Directorate was responsible for training of Space Station *Freedom* crew and ground controllers and for around-the-clock operational support of the Space Station. Kennedy Space Center was responsible for processing of payloads for flights to *Freedom* on the Shuttle. This included the required assembly, servicing, integration and testing of payload hardware and software, and the requisite operations associated with a Shuttle launch. Contractors were responsible for design; development; testing; evaluation; operation of hardware and software systems; and element, evolution, and engineering support. A number of international partners were also providing various Station elements. Figure 3–13 maps the three Work Packages and the contributions of the international partners with the various Space Station *Freedom* elements as published the 1992 Space Station Freedom Strategic Plan.[26]

At this time, the Level II program office headed by Richard Kohrs was located at NASA Headquarters. On December 1, 1992, NASA announced its intention to consolidate some management functions and move the Headquarters-based program office, led by Kohrs, to Reston, Virginia. NASA also announced that the Agency would create a contractor-led joint vehicle integration team based at Johnson Space Center and staffed by the three Space

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[25] *Space Station Freedom Media Handbook*, 1992, p. 8. Goddard Space Flight Center and its prime contractor, GE Astro-Space, originally were to manufacture the servicing facility, the flight telerobotic servicer, accommodations for attached payloads, and the U.S. uncrewed free-flyer platforms. However, in 1991, these elements were either terminated or transferred to other NASA organizations, and this Work Package was dissolved.

[26] *NASA Space Station Freedom Strategic Plan 1992* (undated), p. 19 (NASA History Office Folder 16941).

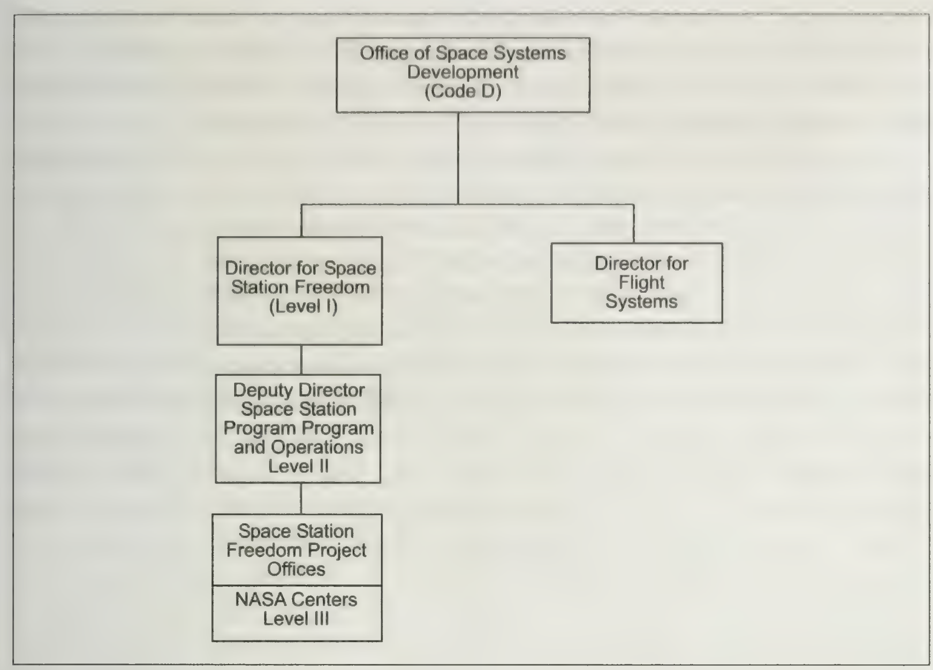
Office of Space Systems Development (Code D)
Director for Space Station Freedom (Level I)
Director for Flight Systems
Deputy Director Space Station Program Program and Operations Level II
Space Station Freedom Project Offices
NASA Centers Level III

Figure 3–12. Space Station Freedom *Three-Level Program Management, 1992.*

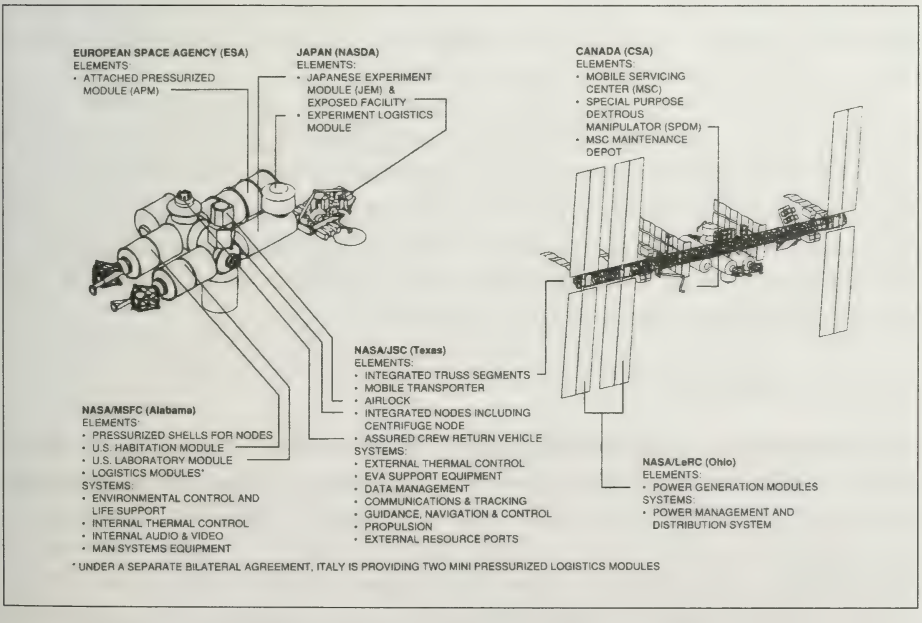
EUROPEAN SPACE AGENCY (ESA)
ELEMENTS:
• ATTACHED PRESSURIZED MODULE (APM)
JAPAN (NASDA)
ELEMENTS:
• JAPANESE EXPERIMENT MODULE (JEM) & EXPOSED FACILITY
• EXPERIMENT LOGISTICS MODULE
CANADA (CSA)
ELEMENTS:
• MOBILE SERVICING CENTER (MSC)
• SPECIAL PURPOSE DEXTROUS MANIPULATOR (SPDM)
• MSC MAINTENANCE DEPOT
NASA/JSC (Texas)
ELEMENTS:
• INTEGRATED TRUSS SEGMENTS
• MOBILE TRANSPORTER
• AIRLOCK
• INTEGRATED NODES INCLUDING CENTRIFUGE NODE
• ASSURED CREW RETURN VEHICLE
SYSTEMS:
• EXTERNAL THERMAL CONTROL
• EVA SUPPORT EQUIPMENT
• DATA MANAGEMENT
• COMMUNICATIONS & TRACKING
• GUIDANCE, NAVIGATION & CONTROL
• PROPULSION
• EXTERNAL RESOURCE PORTS
NASA/MSFC (Alabama)
ELEMENTS:
• PRESSURIZED SHELLS FOR NODES
• U.S. HABITATION MODULE
• U.S. LABORATORY MODULE
• LOGISTICS MODULES*
SYSTEMS:
• ENVIRONMENTAL CONTROL AND LIFE SUPPORT
• INTERNAL THERMAL CONTROL
• INTERNAL AUDIO & VIDEO
• MAN SYSTEMS EQUIPMENT
NASA/LeRC (Ohio)
ELEMENTS:
• POWER GENERATION MODULES
SYSTEMS:
• POWER MANAGEMENT AND DISTRIBUTION SYSTEM
* UNDER A SEPARATE BILATERAL AGREEMENT, ITALY IS PROVIDING TWO MINI PRESSURIZED LOGISTICS MODULES

Figure 3–13. Space Station Freedom *Work Package and International Partner Development Responsibilities.*[27]

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[27] *Space Station Freedom Media Handbook*, 1992, p. 22.

Station prime contractors—Boeing, McDonnell Douglas, and Rocketdyne—and Grumman's Space and Electronics Group, which had an engineering and integration contract with the office in Reston, Virginia. The team would ensure the "successful building and deployment" of the Space Station.[28]

In early 1993, President William J. Clinton called for NASA to redesign the Space Station, reducing the complexity of both the Station itself and its management structure to reduce cost and produce greater returns on NASA's investment.[29] In March, Administrator Goldin announced a number of changes relating to the redesigned Station, given the name Space Station *Alpha*. These changes affected the Station's management as well as its workforce level and location. In July, Goldin announced that Bryan O'Connor would head the Space Station transition to the redesigned Station. Goldin also stated that the number of civil servants needed for the Space Station would be reduced from approximately 2,300 to 1,000. At the same time, NASA announced that it would recruit 300 positions to staff the new Space Station Program Office at a host Center "yet to be determined." In August, Goldin announced the selection of Johnson Space Center in Houston, Texas, as host Center and Boeing as the prime contractor. The new program office had all implementation responsibilities: the design, development, and the physical and analytical integration of the Space Station as the program evolved into operations. The new organization structure would have about 1,000 civil servants, consisting of about 300 civil servants at the program office at Johnson and the other 700 positions spread among all involved NASA Centers, including Johnson.[30] Approximately 800 Space Station contractors working near the Reston office either lost their jobs or were invited to relocate.

In September 1993, Space Station Director Kohrs retired from NASA. In October, Goldin announced that the Space Station program would move from the Office of Space Systems Development (Code D) back to the Office of Space Flight (Code M). Jeremiah W. Pearson III managed the integration of the two programs. William Shepherd became Space Station Program Manager at Johnson Space Center. O'Connor, Director of the Space Station transition, was named acting Space Station Program Director.

Phase III: 1994–1998

A number of management changes took place in January 1994 as Space Station *Alpha* transitioned into the ISS. Wilbur C. Trafton became Deputy Associate Administrator for the Space Station.[31] Trafton was assisted by

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[28] "Management Changes Made to Space Station Program," *NASA News* Release 92–214, December 1, 1992 (NASA History Office Folder 009610).

[29] "Organizational Changes to Enhance Programs, Relations," *NASA News* Release 93–044, March 11, 1993. "Special Announcement," March 11, 1993 (NASA History Office Folder 009610).

[30] "Space Station Host Center and Prime Contractor Announced," *NASA News* Release 93–148, August 17, 1993 (NASA History Office Folder 009610).

[31] Trafton was the sixth person to run the Space Station program since it began in 1984. His predecessors were John Hodge, Philip Culbertson, Andrew Stofan, James Odom, and most recently, Richard Kohrs.

Randy Brinkley at Johnson Space Center in Houston, Texas. Brinkley was appointed Space Station Program Manager responsible for managing all United States-Russian activities and working with Russia to implement United States-Russian activities for Phase I and Phase II of the Space Station program.[32] William Shepherd was named Deputy Program Manager at Johnson. Pamela McInerney served as acting head of the Space Station Headquarters Office during much of 1994. After McInerney left the position, it remained vacant until Joyce Carpenter took the position in early 1995. She was replaced in the fall of 1995 by Gretchen McClain.

In October 1995, the Office of Space Flight reorganized with the goal of simplifying its structure and increasing its organizational efficiency. Figure 3–14 shows its structure in October 1995.

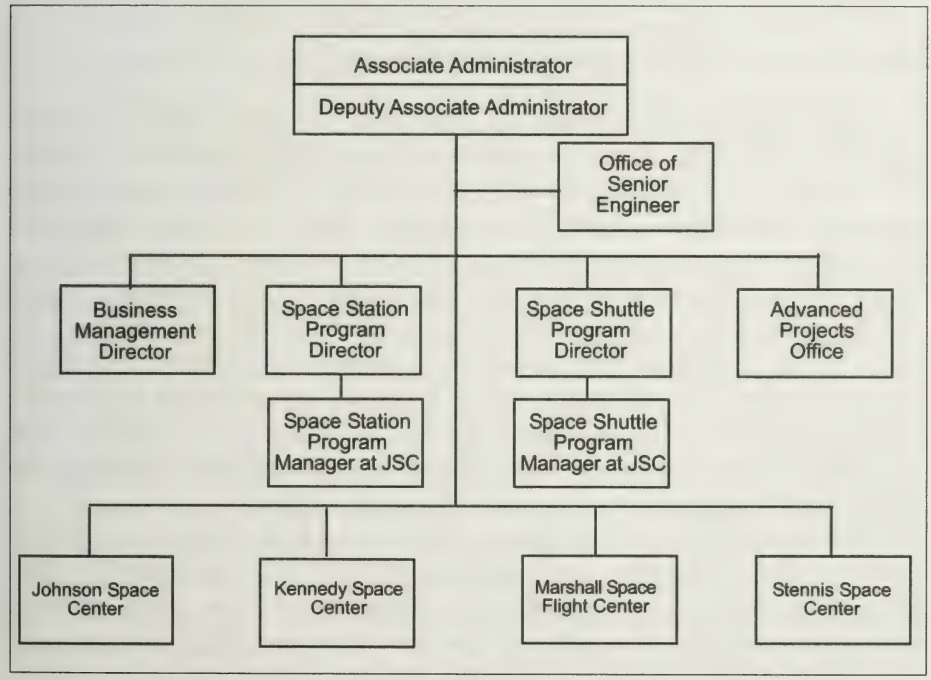
Associate Administrator
Deputy Associate Administrator
Office of Senior Engineer
Business Management Director
Space Station Program Director
Space Shuttle Program Director
Advanced Projects Office
Space Station Program Manager at JSC
Space Shuttle Program Manager at JSC
Johnson Space Center
Kennedy Space Center
Marshall Space Flight Center
Stennis Space Center

Figure 3–14. Office of Space Flight (Code M), October 1995.

In January 1996, Trafton assumed additional responsibilities, first becoming acting Associate Administrator for the Office of Space Flight at NASA Headquarters and then Associate Administrator in March. Andrew Allen became acting Space Station Program Director until Gretchen McClain took over in January 1997. Other changes at the same time included naming William Shepherd Deputy Manager for Space Station International Affairs to lead the integration of all Russian issues for the Station. Douglas Cooke, Manager of the Vehicle Office, was named acting Deputy Manager for the program. Denny Kross took Cooke's place as acting Manager of the Vehicle Office, and Lauri Hansen was named acting Deputy Manager of the Vehicle Office.[33] In June, Program Manager Randy Brinkley established three new positions to help prepare for launch and flight operations: Kevin Chilton became Deputy for operation, Douglas Cooke was named Deputy for technical development, and Dan Tam became acting Deputy for business management.[34]

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[32] Phase I and Phase II of the Space Station program consisted of the Shuttle-*Mir* flights and the first set of Space Station assembly flights. See the detailed description of Space Station development later in this chapter.

In November 1997, Trafton resigned from NASA, leaving his position as Associate Administrator of the Office of Space Flight. In January 1998, Administrator Goldin named Joseph Rothenberg, Director of Goddard Space Flight Center, to the job. Rothenberg became NASA's fourth human spaceflight Associate Administrator in little more than three years, closing out this decade.

Life Sciences and Microgravity Sciences Management

Life sciences and microgravity sciences were closely tied to human spaceflight. The 1992 Space Life Sciences Strategic Plan stated that NASA's life sciences program "significantly contributed to NASA's manned and unmanned exploration of space" during the last 30 years. The plan also stated that the life sciences program maintained a "close working relationship with the Office of Space Flight on operational issues dealing with crew health . . .[and] with the newly formed Office of Space Systems Development in conducting the research and development to support the operation and utilization of Space Station *Freedom* . . ."[35] Similarly, later in the decade, when NASA adopted the enterprise approach to organize its themes, the Microgravity Sciences and Applications Division and the Microgravity Research program supported the Human Exploration and Development of Space Enterprise.

Until early 1993, the Life Sciences Division was located within NASA's Office of Space Science and Applications. The Life Sciences Division focused on activities that dealt with understanding how living systems responded to the space environment; the search for the origin, evolution, and distribution of life in the universe; the development of the scientific and technological foundations for expanding the human presence beyond Earth orbit and into the solar system; and providing operational medical support to all space missions involving humans. Results from the division's research helped maintain astronaut health and productivity, understand the response of biological mechanisms to weightlessness, and design controlled ecological life support systems.[36] In 1989, Arnauld Nicogossian led the division, having become its head in 1983.

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[33] "Space Station Office Makes Managerial Changes," *Space News Roundup*, Johnson Space Center (January 12, 1996): p. 1 (NASA History Office Folder 009610).

[34] "Brinkley Establishes Key Management Positions," *Space News Roundup*, Johnson Space Center (June 24, 1996): p. 4 (NASA History Office Folder 009610).

[35] *Space Life Sciences Strategic Plan, 1992*, National Aeronautics and Space Administration, Space Life Sciences.

The Microgravity Science and Applications Division was also a division within the Office of Space Science and Applications. It appeared as a budget line within the larger Materials Processing in Space budget category. The division aimed to foster the development of near-Earth space as a natural resource by exploiting microgravity and other unique attributes that might be attained in an orbiting spacecraft. From 1989 to 1991, the division was led by acting Director Robert Schmitz. In 1991, Robert Rhome was appointed Division Director.

In March 1993, in a series of organizational changes, Administrator Goldin announced a new Office of Life and Microgravity Sciences and Applications (OLMSA), designated Code U. The new office was to "assure the right emphasis in the [Space Station] redesign effort . . . The redesigned Space Station must provide for significant long duration space research in materials and life sciences during this decade." It was also responsible for instituting NASA policies and procedures for the protection of human research subjects.[37]

Harry Holloway was appointed the first OLMSA Associate Administrator, and Nicogossian was appointed OLMSA Deputy Associate Administrator for spaceflight activities, moving from his position as Chief Medical Officer in the Office of Space Flight.[38] Rhome continued leading the Microgravity Sciences and Applications Division, which moved from the Office of Space Sciences and Applications to OLMSA. The division's focus was to increase understanding of the effects of gravity on biological, chemical, and physical systems using both spaceflight and ground-based experiments. Joan Vernikos became head of the Life and Biomedical Sciences and Applications Division in the Microgravity Division, and Edmond Reeves was appointed initially as acting head of the Flight Systems Division and then as Division Director in 1994. In mid-1993, the Occupational Health and Aerospace Medicine Division, led by Marshall S. Levine, was added to OLMSA. Earl Ferguson took over leadership of the Occupational Health and Aerospace Medicine Division on an acting basis in the spring of 1994 when Levine became Director of the Occupational Health Office.

In May 1996, Holloway left his position, and Nicogossian became initially the new acting OLMSA Associate Administrator and then Associate Administrator in June 1997. Beth McCormick became Deputy Associate Administrator. In early 1997, James Collier was appointed the new head of the Aerospace Medicine Division, which had split off from the Division of

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[36] "Estimates Life Sciences Program Budget Summary," Research and Development Fiscal Year 1989 p. RD 4–2.

[37] NASA Management Instruction 7100.8B "Protection of Human Research Subjects", August 8, 1995.

[38] "Organizational Changes to Enhance Programs, Relations," *NASA News Release 93–044*, March 11, 1993. Also "Special Announcement," March 11, 1993 (NASA History Office Folder 009610).

Occupational Health and Aerospace Medicine Division. The Space Development and Commercial Research Division, led by Edward Gabris, was also established. In 1998, Richard Williams moved to lead the Aerospace Medicine Division; Mark Uhran became acting head of the Flight Systems Office; and Raymond Whitten replaced Gabris as head of the Space Development and Commercial Research Division.

Money for Human Spaceflight

This section discusses funding for Spacelab, Space Station, and life and microgravity sciences. The budget tables that follow show budget requests and programmed amounts for NASA's human spaceflight programs (other than the Space Shuttle, which is addressed in chapter 2, Launch Systems). Since NASA typically submits an original and revised budget request before Congress acts on a budget, both amounts are indicated and separated by a forward slash. Where no amount appears, there was no submission. Programmed amounts are determined after the end of a fiscal year and reflect the amounts actually available to be spent. Occasionally, a budget category is established during a fiscal year. When this happens, there will be a programmed amount shown but no budget request for that budget category. Funds for these activities often were transferred from another project's budget through a "reprogramming" of funds during the year. All amounts come from the annual budget requests prepared by the NASA Office of the Chief Financial Officer.

Spacelab

Spacelab funds were included in the Space Transportation Capability Development budget category in the Research and Development and Human Spaceflight appropriations. Some Spacelab funding also came from the Shuttle/Spacelab Payload Mission Management and Integration budget category and from various life and microgravity sciences budget categories. Spacelab development funding supported space-based and ground support equipment and hardware to expand Spacelab capabilities and ensure its continued operational availability. Spacelab operations support funding included mission planning and integration and flight and ground operations. It also funded smaller payloads including the Get Away Specials and Hitchhiker payloads.

The level of funding for Spacelab generally corresponded with the number and complexity of scheduled Spacelab missions and whether funds would be received from other Spacelab participants, such as Japan and Germany. The final Spacelab mission occurred in April 1998, and funds for Spacelab began to fall in FY 1997 and were reduced to a very low level in FY 1998.

Space Station

Funding for the Space Station mirrored the contentiousness of the entire program. President Ronald Reagan first proposed the program, and although it generally received support from later presidents, members of Congress continued to question the validity of the program and the advisability of spending large sums of money on a program whose scientific and political benefits were doubtful. They also questioned NASA's dependence on the contributions and cooperation of international partners who had their own financial and political problems, particularly Russia. Thus, in almost every session of Congress, motions were introduced to cancel the program; although all of these motions were defeated, on one occasion, the margin to continue the program was only a single vote. Congress kept an extremely close eye and tight rein on the program, generally providing only one year of funding at a time and requiring NASA to annually justify new funding requests.

The Space Station took a large portion of NASA's Research and Development and HSF appropriated funds, reaching a high of 42 percent in FY 1998 (see Table 3–1). This spending caused some resentment among the science community, as some considered the research benefits of the orbiting laboratory limited. From FY 1989 to FY 1998, funds appropriated annually for the Space Station grew from a low of $900 million to a high of almost 2.4 billion, a factor of more than two and one-half. This growth occurred even though redesigns reduced the size and complexity of the Station. The funding need brought Russia into the partnership to assume some of the expenses. The Space Station also received some funding from the Science, Aeronautics and Technology appropriation (not reflected in this table), which effectively increased the percent of the total NASA budget dedicated to the program.

In 1993, President William J. Clinton ordered NASA to redesign the Space Station to reduce program costs while still providing significant research capabilities. The chosen redesign came with a total budget cap of $17.4 billion and a fixed annual budget of $2.1 billion, although these limits were not set in law. The President's annual cap was below the annual ceiling of $2.8 billion identified by NASA Station designers in their three proposed design options. To accommodate the lower ceiling but stay within the $17.4 billion total, NASA regularly slipped the delivery dates for both individual elements and a completed Station.

Beginning in 1995 when NASA's appropriation categories were restructured and the Research and Development appropriation category was eliminated, Space Station-related activities were funded from the HSF and the Science, Aeronautics and Technology appropriations. Activities funded in the HSF appropriation included the development and operation of the Space Station and the flight support component of the Russian cooperation program of joint flights to *Mir*. Space Station-related funding from the Science

Aeronautics and Technology appropriation provided for development, operation, and science research associated with the scientific, technology, and commercial payloads being built for Space Station use or in conjunction with the Mir program. The largest amount came from the Office of Life and Microgravity Sciences and Applications to fund its experiments. In addition, the Mission to Planet Earth program (NASA's Earth Sciences program) provided funds for an externally attached Space Station payload, and the Space Access and Technology program provided funds for technology and commercial payloads for both external and pressurized Space Station deployment.[39] When including all of these sources of funds, as well as the amount allowed in a new contingency account called Russian Cooperation and Program Assurance and some funds in the Construction of Facilities account used for the Space Station, funding for the Station remained fairly steady through 1997 and even rose slightly.

Money problems, however, did not abate. In September 1997, Boeing admitted it was incurring millions of dollars in cost overruns and could have a $600 million overrun at Station completion.[40] NASA also accepted some of the conclusions of the Cost Control Task Force (except for a cost estimate of $24.7 million at completion), chaired by Jay Chabrow, and raised the cost to complete to $22.7 billion.[41] NASA requested an increase of $430 million in the appropriation for FY 1998. Congress responded with $230 million. At the end of the decade, additional funds would be needed for NASA to complete the Space Station, whether they came from Congress or were diverted from other NASA programs.

Table 3–2 shows authorized and appropriated amounts for Research and Development, HSF, and the Space Station from 1989–1998. Table 3–3 shows the programmed amounts for the budget categories included in this chapter. If no programmed amount appears for a particular budget category or for a particular year, there was no amount indicated in the budget documents. Tables 3–4 through 3–43 show the amounts requested by NASA and the programmed amounts. Where the authorization or the appropriation was listed, those amounts are provided. As explained in chapter 1, NASA submits an initial and a revised budget request to Congress before the budget is passed. Where available, both amounts are indicated in the column titled Budget Submission with the two amounts separated by a forward slash. The programmed amount indicates the amount actually spent.

The move toward implementation of "full-cost" accounting, which NASA began with the FY 1997 budget request, aimed to give a more accurate picture of actual project costs. This method of accounting associated all project costs in project budgets, regardless of their source. Starting with projected FY 1997 costs, that is, the budget request, NASA showed budget figures using both the traditional method being phased out and the new "full-cost" method. FY 1995 and prior years' budget authority were recalculations reflecting the full cost of all elements associated with a project.[42] Where provided in budget documents, the following tables show an amount for "budget authority" as stated in the FY 1998 budget estimate. In this budget estimate, NASA restated the amounts estimated for the Space Station to include the funds appropriated in FY 1997 and prior years to the current Science, Aeronautics, and Technology, former Construction of Facilities, and former Research and Development appropriations as well as funds appropriated in the HSF appropriation. The amounts from appropriations other than HSF are shown only in the "Space Station-Research" budget category.[43]

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[39] "Analysis of Agency Support for International Space Station," *National Aeronautics and Space Administration Fiscal Year 1997 Estimates,* p. SI–2.

[40] Smith, *Space Stations,* 1999, p. CRS–6.

[41] NASA Advisory Council, "Report of the Cost Assessment and Validation Task Force on the International Space Station," April 21, 1998, *http://history.nasa.gov/32999.pdf* (accessed June 12, 2005).

The Space Shuttle

This section describes the Space Shuttle system and operations and details of each Shuttle mission between 1989 and 1998. For an overview of the Shuttle's development and a detailed description of events of the prior decade, the reader may consult the *NASA Historical Data Book, Volume V, 1979–1988.*[44] As in the previous chapter, all measurements are given in the unit used in the original reference. Equivalent measurements in alternate units follow in parentheses.

The Space Shuttle system consisted of four main components: an expendable external tank, two reusable solid rocket boosters, a reusable orbiter, and three installed main engines, commonly called the Space Shuttle Main Engines (see Figure 3–15).[45] The structure and systems of the Space Shuttle have remained essentially the same since its inception. Detailed descriptions of its components and systems are available in the *NSTS Shuttle Reference Manual* (1988) and in the *Shuttle Crew Operations Manual*.[46]

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[42] Budget authority represents the amounts appropriated by Congress in a given fiscal year that provides NASA with the authority to obligate funds. Obligation of funds legally commits NASA to pay contractors and other service providers for materials and services. The ensuing obligations, cost incurrence, and expenditures (outlays) based on the budget authority can occur in a different fiscal year from the year in which Congress provides the budget authority.

[43] "Full-Cost Budgeting," National Aeronautics and Space Administration Fiscal Year 1998 Budget Estimates, pp. SI–6–SI–7.

[44] Judy Rumerman, compiler, *NASA Historical Data Book, Volume V, 1979–1988* (Washington, DC: National Aeronautics and Space Administration Special Publication-4012, 1999), pp. 121–238, 269–358. Also at *http://history.nasa.gov/SP-4012/vol5/cover5.html.*

[45] The external tank, solid rocket boosters, and main engines are described in chapter 2, Launch Systems, of this volume.

[46] *NSTS Reference Manual, 1988, http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/stsref-toc.html* (accessed July 6, 2005); *Shuttle Crew Operations Manual,* OI–29, SFOC-FL0884, Rev. B, CPN-3, United Space Alliance (January 13, 2003).

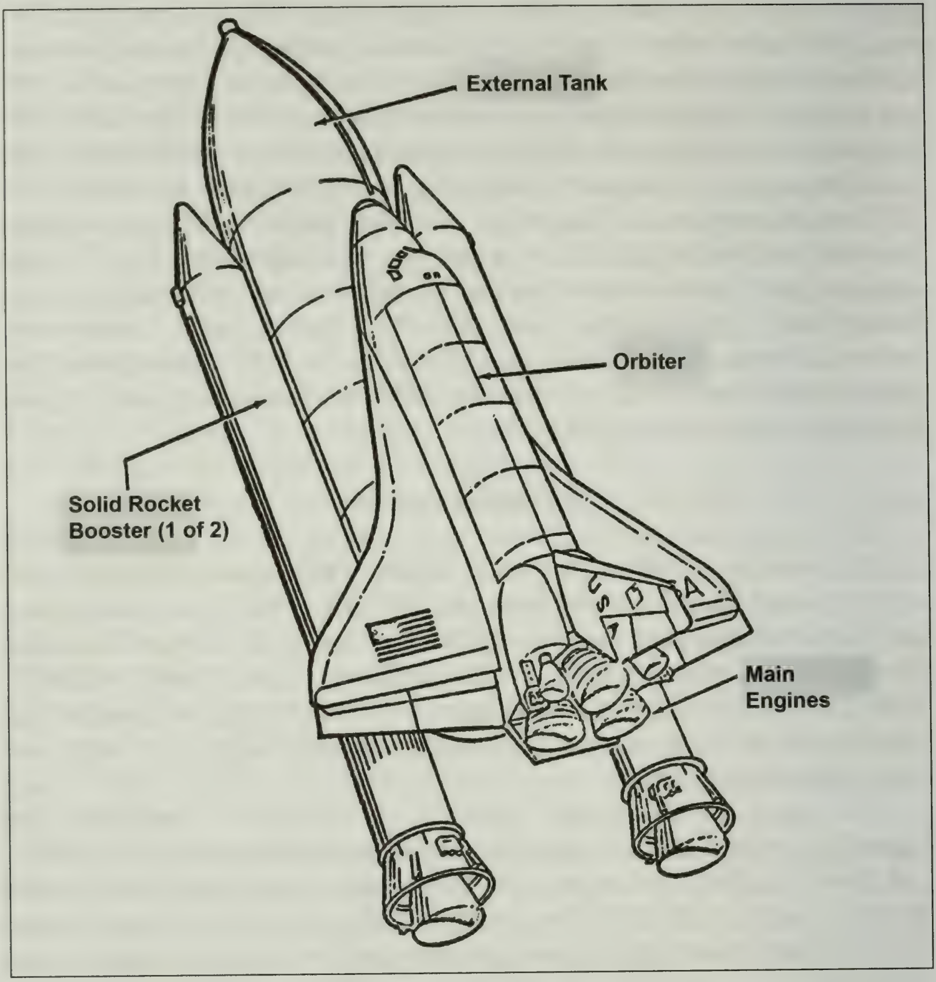

Figure 3–15. Space Shuttle Vehicle Configuration.[47]

The Space Shuttle could perform a variety of missions. These included:

- Delivery of payloads to specified Earth orbits.
- Placement of payloads into parking orbits for subsequent transfer to other orbits or Earth escape trajectories.
- Rendezvous and stationkeeping with detached payloads/space stations.
- Monitoring and checkout of payloads.
- Return of payloads to Earth from a specified orbit.
- Routine and special support to space activities such as sortie missions; rescue; repair; maintenance; servicing; assembly; disassembly; and docking.
- Space Station assembly and operations support.

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[47] "Space Shuttle Program Description and Requirements Baseline," NSTS 07700, Vol. I, Rev. G, December 17, 1997, pp. 3–15, *http://pbma.hq.nasa.gov/sma/public/Jsc/bp_jsc_44.pdf* (accessed June 28, 2005).

The Shuttle could transport payloads into near-Earth orbit 100 nautical miles to 312 nautical miles (185 kilometers to 578 kilometers) above Earth. Acceleration during ascent never exceeded 3g. On its return to Earth, the orbiter had a crossrange maneuvering capability of about 550 nautical miles (1,019 kilometers) either side of center. The orbiter normally carried crews of up to seven people, although it could carry eight-person flight crews. The usual mission lasted from 4 to 16 days in space.

All Shuttle flights launched from Kennedy Space Center in Cape Canaveral, Florida. The Kennedy and Edwards Air Force bases in California were the primary landing sites. Contingency landing sites were also provided in the event the orbiter needed to return to Earth in an emergency.

On a typical mission, payload bay doors were opened soon after orbit stabilization to allow the orbiter space radiators to dissipate heat. The crew then conducted payload operations from the payload station on the aft flight deck. Upon completion of on-orbit operations, the payload bay doors were closed, and the orbiter was configured for return to Earth. The orbiter returned to Earth by firing the orbital maneuvering system engines to reduce velocity. After reentering Earth's atmosphere, the orbiter glided to its landing at Kennedy Space Center or, if conditions prevented landing at Kennedy, at Edwards Air Force Base. The incorporation of a drag chute and carbon-carbon brakes allowed more missions to land at Kennedy.

Shuttle Orbiter

For most of this decade, the Shuttle orbiter fleet consisted of four vehicles. *Columbia* (OV-102), the first operational orbiter; *Discovery* (OV-103), and *Atlantis* (OV-104) were part of the original orbiter fleet. *Endeavour* (OV-105) replaced the *Challenger* in 1992.

The orbiter was comparable in size and weight to a modern commercial airliner. It had three main engines and two smaller solid orbital maneuvering system engines mounted in the rear that assisted during initial phases of the ascent trajectory. The main engines provided the vehicle acceleration from liftoff to main engine cutoff at a predetermined velocity. In space, the reaction control system engines provided attitude control. Figure 3–16 shows the orbiter's structure.

The orbiter was constructed primarily of aluminum. A thermal protection system made of rigid silica tiles or some other heat-resistant material shielded every part of its external shell and protected it from reentry heat. Tiles covering the upper and forward fuselage sections and the tops of the wings could absorb heat as high as 650°C (1,202°F). Tiles on the underside absorbed temperatures up to 1,260°C (2,300°F). Panels made of reinforced carbon-carbon covered areas that had to withstand temperatures greater than 1,260°C (2,300°F), such as on the nose and leading edges of the wings on reentry.

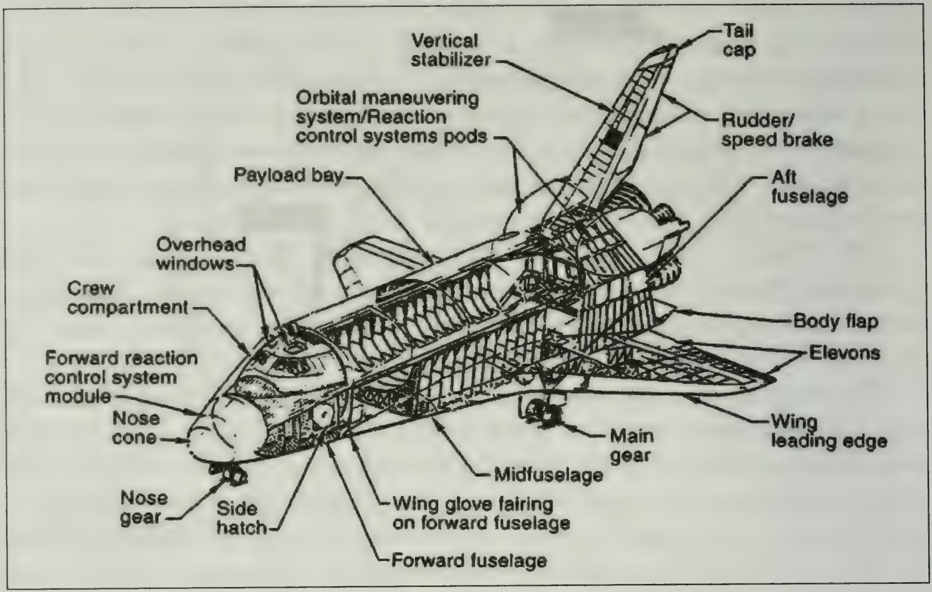
Vertical stabilizer
Tail cap
Orbital maneuvering system/Reaction control systems pods
Rudder/ speed brake
Payload bay
Aft fuselage
Overhead windows
Crew compartment
Body flap
Elevons
Forward reaction control system module
Nose cone
Wing leading edge
Main gear
Midfuselage
Nose gear
Side hatch
Wing glove fairing on forward fuselage
Forward fuselage

Figure 3–16. Orbiter Structure.[48]

The orbiter structure had nine major sections:

1. The forward fuselage consisting of upper and lower sections that fit clamlike around a pressurized crew compartment
2. Wings
3. Midfuselage
4. Payload bay doors
5. Aft fuselage
6. Forward reaction control system
7. Vertical tail
8. Orbital maneuvering system/reaction control system pods
9. Body flap

Table 3–44 lists nominal orbiter characteristics. The individual mission tables later in this chapter include characteristics for each mission.

Endeavour, NASA's fifth operational orbiter, was the newest addition to the Shuttle fleet. Congress authorized NASA to construct *Endeavour* on August 1, 1987. Table 3–45 lists *Endeavour*'s construction milestones. *Endeavour* was named through a national competition involving students in elementary and secondary schools who were asked to select a name based upon an exploratory or research sea vessel. President George H. W. Bush announced the winning name in May 1989. *Endeavour* entered service on May 7, 1992, on the STS-49 mission.

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[48] *Shuttle Crew Operations Manual*, p. 1.2–1.

Endeavour incorporated a number of upgrades. They included:

- A 40-foot (12.2 meter)-diameter drag chute that reduced the orbiter's rollout distance by 1,000 feet to 2,000 feet (305 meters to 610 meters).
- An updated avionics system including advanced general purpose computers, improved inertial measurement units and tactical air navigation systems, enhanced master events controllers and multiplexer-demultiplexers, and a solid-state star tracker.
- Improved nosewheel steering mechanisms.
- An improved version of the auxiliary power units providing power to operate the Space Shuttle's hydraulic systems.
- A ground cooling hookup to allow the payload bay to cool the mini-pressurized logistics module.
- Doublers on several wing spars to allow heavier payloads and two wing glove truss tubes having increased wall thickness.

Endeavour was originally equipped as the first extended duration orbiter. This feature was removed during its Orbiter Maintenance Down Period (OMDP) to save weight for ISS missions. During an OMDP, an orbiter is inspected, torn down, overhauled, and upgraded.

Orbiter Upgrades

Many of the improvements incorporated in the *Endeavour* were made to the other orbiters. Some changes, called Category I changes, were required before the return to flight in 1988. Others were made when the orbiters came out of service for regular maintenance and modifications. A number of improvements outfitted the orbiters for visiting the Space Station.

Columbia was the oldest orbiter and the first to undergo a scheduled inspection and retrofit program. It received modifications at the Rocketdyne Division of Rockwell International assembly plant at Palmdale, California, where it had been manufactured, after completion of STS-4, after STS-5, and after STS-9. These modifications added equipment needed to accommodate the PAM to be used for the STS-5 payload and to allow it to accommodate the Spacelab. They also removed the ejection seats, installed Orbiter Experiments Program packages and heads-up displays, and added provisions for GPS navigation, as well as more than 200 other modifications.[49]

On August 10, 1991, after completion of STS-40, *Columbia* returned to Palmdale, California. The spacecraft underwent approximately 50 upgrades there, including the addition of carbon brakes, a drag chute, and improved nose wheel steering; removal of instrumentation used during the test phase of the orbiter; and an enhancement to its thermal protection system. The orbiter returned to Kennedy Space Center in February 1992. On October 8, 1994, *Columbia* went back to Palmdale, California for its first OMDP. Approximately 90 modifications and upgrades were made during a six-month period. Modifications included upgrades to the main landing gear thermal barrier; tire pressure monitoring system, and radiator drive circuitry. Repairs were made to the radiators where micrometeorites had made impacts. Intensive structural inspections took place, and an upgraded corrosion control coating was applied on the wings and rudder. This overhaul left the vehicle in "like-new" condition. *Columbia* was too heavy to fly either to the Russian *Mir* space station or to perform Space Station assembly missions and was not retrofitted for that purpose.

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[49] Dennis R. Jenkins, *Space Shuttle: The History of the National Space Transportation System, The First 100 Missions*, 3rd ed. (Cape Canaveral, FL: Dennis Jenkins, 2001), pp. 435–437.

Discovery's first OMDP took place beginning in mid-March 1992 after its return to Kennedy Space Center from Edwards Air Force Base where the STS-42 mission landing took place. A drag chute was installed, and the orbiter received a complete structural inspection and refurbishment of the thermal protection system.[50]

Its next inspection was in 1995. *Discovery* departed from Kennedy on September 27, 1995, arriving at Palmdale, California, to undergo a nine-month OMDP. The vehicle was outfitted with a fifth set of cryogenic tanks, and an external airlock replaced its internal airlock. This gave it the capability to participate in Shuttle-*Mir* docking missions and support missions to the ISS. *Discovery* left Palmdale for its return to Kennedy, riding atop a modified Boeing 747, on June 28, 1996.

Atlantis's first OMDP extended from October 1992 through May 1994 while major work required for *Atlantis* to support missions to *Mir* took place. Modifications included installation of a drag chute, new plumbing lines and electrical connections enabling extended duration missions, improved nosewheel steering, new insulation for the main landing gear doors, more than 800 new heat protection tiles and blankets, and structural modifications to the airframe. *Atlantis* received an Orbiter Docking System, which included both Russian and U.S. hardware.

Atlantis's second OMDP began in November 1997 at Boeing's facility in Palmdale, California, where about 130 modifications were made.[51] Along with detailed nose-to-tail inspections and replacement of dated flight hardware, workers installed thinner and lighter insulation that reduced the orbiter's weight by about 1,000 pounds (454 kilograms), allowing the orbiter to haul heavier cargo into space. An external airlock replaced its internal airlock, freeing up interior space in the middeck and equipping it for ISS docking rather than for docking with *Mir*. The Multifunctional Electronic Display System, or "glass cockpit," replaced the cockpit's four cathode ray tube screens, mechanical gauges, and instruments with full-color, flat-panel displays like those used on modern commercial airliners and military aircraft. The orbiter left Palmdale, California, on September 24, 1998, arriving at Kennedy on September 27.

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[50] "Chronology of KSC and KSC Related Events for 1992," Part I at *http://www-lib.ksc.nasa.gov/lib/archives/chronologies/1992CHRONO1.pdf*, Part II at *http://www-lib.ksc.nasa.gov/lib/archives/chronologies/1992CHRONO2.pdf* (accessed July 6, 2005).

[51] "Space Shuttle *Atlantis* Modification Work To Be Performed at Palmdale Facility," *NASA News* Release 97–11, January 16, 1997, *http://www.nasa.gov/lb/centers/johnson/news/releases/1996_1998/97-11.html* (accessed April 28, 2005). Also "Atlantis Scheduled To Return to KSC after 10 Months in Palmdale, CA," *NASA News*, Kennedy Space Center (September 21, 1998), *http://xs4all.nl/~carlkop/atlantis.html* (accessed April 14, 2006). In 1996, Rocketdyne became part of the Boeing Company.

Endeavour's eight-month OMDP in Palmdale, California, began at the end of July 1996. About 100 modifications were performed. Approximately 10 of those modifications were directly associated with work required to support ISS operations. The most extensive modification was the installation of an external airlock equipped with fluid and power lines to support spacewalks that replaced the original internal airlock. Other modifications included upgrades to the orbiter's power supply system; general purpose computers; the thermal protection system; installation of new, lightweight commander and pilot seats; other weight-saving modifications; and a number of safety and turnaround enhancements.

Payload Accommodations

Shuttle payloads ranged in size from those like the Hubble Space Telescope that weighed thousands of pounds to small payloads weighing less than 60 pounds (27 kilograms). The Shuttle provided several types of payload accommodations including the payload bay and crew compartment, payload carriers, and pressurized modules. For payloads carried in the payload bay, structural supports enabling payloads to withstand the rigors of liftoff and ascent to orbit were provided by main frames below the longeron sills on each side of the bay and by using payload attach fittings placed to suit the payload's dimensions. Large payloads had trunnions that mated directly with the attach fittings. Smaller payloads could be mounted on carriers that fit into the attach fittings. The Shuttle also provided a variety of services including power, thermal control, communications and data handling, and displays and controls for crew interaction, provided through the avionics system.

The Space Shuttle accommodated three basic types of payloads: dedicated, standard, and middeck.[52]

- Dedicated payloads, such as the Spacelab, Hubble Space Telescope, and some DOD payloads, took up the entire cargo-carrying capacity and services of the orbiter. These large payloads occupied the entire payload bay and required the Shuttle's full performance capability.
- Standard payloads were the primary type of Shuttle cargo. Normally, the payload bay could accommodate up to four standard payloads per flight. The avionics system provided power, command, and data services through a standard mixed cargo harness.

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[52] "Mission Preparation and Prelaunch Operations," *NSTS Shuttle Reference Manual (1988), http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/stsover-prep.html* (accessed July 22, 2005).

- Middeck payloads were small, usually self-contained packages requiring a pressurized environment or direct crew operation. They were stored in compartments that could be as small as 2 cubic feet (.06 cubic meter), allowing the opportunity for limited late stowage and early removal from the Shuttle. This type of payload often consisted of manufacturing-in-space or small life sciences experiments.

Displays and controls for payload operations were located in the aft flight deck, which was in the upper level of the crew compartment. The middeck, located immediately below the flight deck, provided the crew living areas and accommodations for middeck payloads. The orbiter payload bay was approximately 60 feet (18.3 meters) long and 15 feet (4.6 meters) in diameter.

The remote manipulator system (RMS) mechanical arm was mounted along the left side of the payload bay. It was used for payload deployment, retrieval, special handling operations, and other orbiter servicing. The RMS was 50.25 feet (15.3 meters) in length.[53]

Table 3–46 lists some of the Shuttle's various payload accommodations.

Small Payloads

The Shuttle carried a variety of small payloads allowing domestic and international educational, commercial, and government payloads to travel into space. The Small Self-Contained Payload (SSCP) program, popularly known as the GAS program, launched its first payload, G-001, on June 27, 1982, on STS-04. G-001 was built by Utah State University. Through 1998, GAS flew 159 payloads on 35 missions.[54] The GAS program was managed by Goddard Space Flight Center.

Standard GAS containers had volumes of 5 cubic feet (0.15 cubic meter) and 2.5 cubic feet (0.07 cubic meter). The 2.5 cubic-foot (0.07-cubic-meter) container could house payloads weighing up to 100 pounds (90.7 kilograms). The larger container could house payloads up to 200 pounds (45.4 kilograms). The GAS carrier provided limited mechanical and electrical interfaces for self-contained experiments, and the customer needed to provide all required battery, data recording, and sequencing systems.[55]

The Code of Federal Regulation, 14 CFR 1214.9, governed the SSCP program and defined and provided the rules for participating in the program. NASA issued the original SSCP rule in 1980. It established conditions of use, reimbursement procedures, and flight scheduling mechanisms for SSCPs flown on the Space Shuttle and ensured equitable allocation of space opportunities to educational, commercial, and U.S. government groups of users.

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[53] "Space Shuttle System Payload Accommodations, Revision L," NSTS 07700, Vol. XIV (2001), pp. 3-1–3-4, 5-10–5-11, *http://shuttlepayloads.jsc.nasa.gov/data/PayloadDocs/documents/07700/Vol_XIV.pdf* (accessed June 1, 2005).

[54] "GAS Can Experiments," *http://members.fortunecity.com/spaceshuttlealmanac/gascans.htm* (accessed 6 July 2005). "Historical Information, Get Away Special," *http://www.wff.nasa.gov/efpo/ssppo/gas/history.html* (accessed April 26, 2005).

[55] "Space Shuttle System Payload Accommodations, Revision L," NSTS 07700, Vol. XIV (2001), p. 5–11.

NASA revised the rule in 1991 and again in 1992, creating 14 CFR 1214.10, "Special Policy on Use of Small Self-Contained Payloads (SSCP) by Domestic Educational Institutions." The revision provided two different pricing structures: an increased standard flight price for commercial and international customers, while the original price remained for domestic educational institutions. On April 23, 1999, NASA revoked both regulations.

In 1995, the SEM program was established to provide students an opportunity to develop experiments not involving complicated engineering. The SEM Carrier System was a self-contained assembly of engineered subsystems functioning together to provide structural support, power, experiment command, and data storage capabilities for microgravity experiments. The system, consisting of a 5-foot (1.5-meter) "canister," contained 10 experiment modules.[56]

The Hitchhiker program became part of the Shuttle Small Payloads Project (SSPP) in 1986. The program expanded GAS capabilities by offering customers power, command, real-time data acquisition and transfer, crew control, and display capability. Hitchhiker customers operated their payloads from the Hitchhiker Control Center at Goddard Space Flight Center using their own ground support equipment (usually a personal computer) to send commands and display data. Users' ground support equipment worked in tandem with Hitchhiker's ground system, the Advanced Carrier Customer Equipment Support System, for communicating with their payloads. Control and monitoring of payloads from remote sites also was used.[57] The first Hitchhiker flight, designated Hitchhiker G-1, took place in 1986 on STS-61-C.

HH-Jr. accommodated experiments requiring power from the orbiter or from internal batteries. A connection to the orbiter enabled the crew to command and check payloads using a laptop computer.

The Hitchhiker carrier system provided electrical power (28 volts DC), command signals, and "downlink" data interfaces. It had provisions for flying payloads along the sidewall of the Space Shuttle payload bay, i.e., the longeron, and on cross-bay carriers/platforms, and provided options for ejecting small spacecraft from the Space Shuttle payload bay. Hitchhiker payloads were contained in mounted canisters attached to mounting plates of various sizes.

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[56] "Space Experiment Module," Fact Sheet, *http://www.wff.nasa.gov/efpo/ssppo/sem/About/about_facts.html* (archived Web site accessed April 26, 2005).

[57] "Hitchhiker Carrier System," *http://www.wff.nasa.gov/efpo/ssppo/hh/index.html* (archived Web site accessed November 15, 2005).

Spacelab

Spacelab was a non-deployable Shuttle payload that carried investigations from many scientific disciplines, including atmospheric science, solar science, materials science, space plasma physics, the life sciences, and astrophysics. Sometimes a Spacelab mission carried experiments from several disciplines; at other times, it focused on a single discipline. Spacelab fit into the Shuttle orbiter's payload bay. Spacelab's modular structure allowed for a wide range of configurations and objectives and enabled extended experiments to take place in orbit (see Figure 3–17). An integral part of the Space Shuttle system, it was developed jointly by ESA and NASA and designed and produced by ESA.[58]

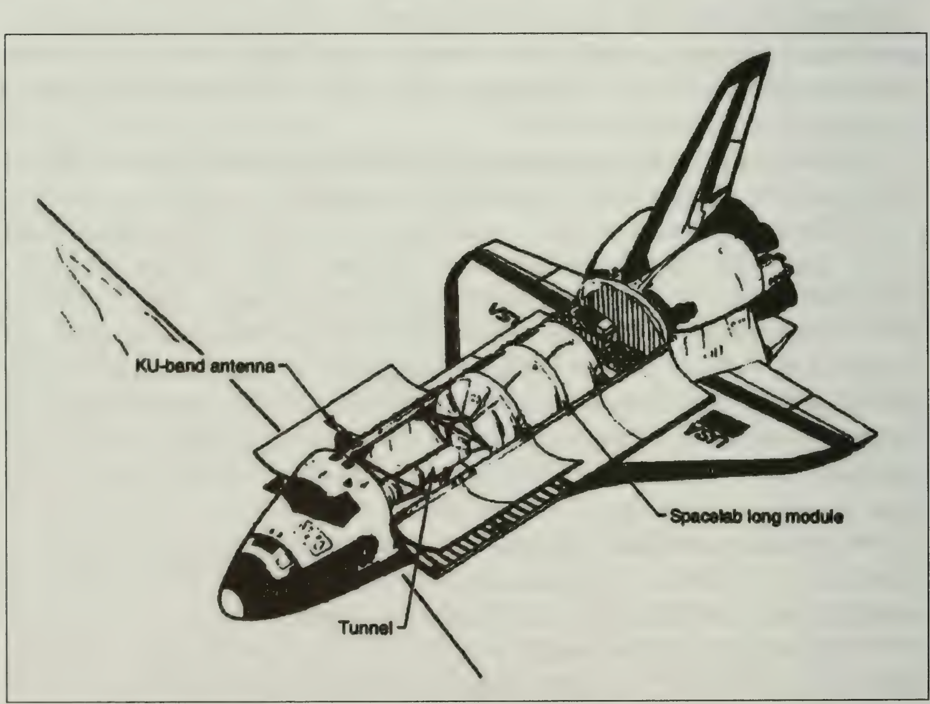

Figure 3–17. Spacelab on Orbit.

Spacelab's four principal components were the pressurized laboratory module, one or more open pallets that exposed materials and equipment to space, a tunnel to gain access to the module, and an instrument pointing system. Electrical power, command and data management, caution and warning, and environmental control and life support systems supported the Spacelab. Figure 3–18 shows Spacelab components. Table 3–47 presents characteristics of the Spacelab module.

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[58] When Spacelab was first proposed, the ESA was called the European Space Research Organisation (ESRO).

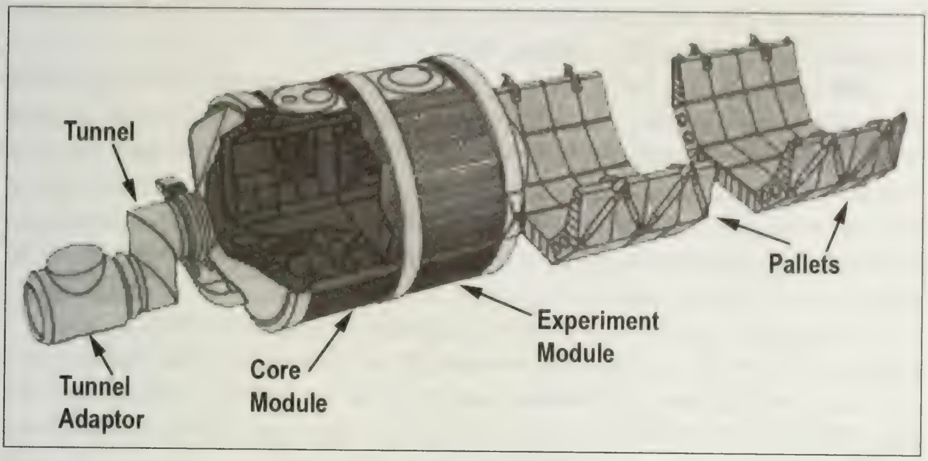

Figure 3–18. Spacelab Components.

The flight crew could control Spacelab experiments from the Spacelab module or from the orbiter's aft flight deck. Experiments located in the module or on the pallets could also be controlled directly from the ground.[59]

The cylindrical pressurized laboratory module had a habitable, shirt-sleeve environment and was available in two segments—a core and an experiment segment—that could be assembled as either a single segment (the core segment) or a double segment (the core and experiment segments, known as the long module). Each segment was 13.5 feet (4.1 meters) in outside diameter and 9 feet (2.7 meters) long. When both segments were assembled with end cones, their maximum outside length was 23 feet (7 meters). The pressurized module was structurally attached to the orbiter payload bay by four attach fittings consisting of three longeron fitting sets (two primary and one stabilizing) and one keel fitting and was covered with passive thermal control insulation. The laboratory equipment was mounted in racks and in other areas. Handrails were mounted in racks, overhead, and on end cones. Foot restraints were also provided on the floor and on rack platforms. Crew objects could be temporarily fastened to Velcro patches throughout the modules.

The core segment (also known as the short module when it was flown alone) contained supporting systems such as data processing equipment and utilities for the module and pallets (if pallets were used with the module). It provided laboratory space with floor-mounted racks and a workbench. When only one segment was needed, the core segment was used. The experiment segment provided more working laboratory space and contained only floor-mounted racks.

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[59] Marsha R. Torr, "Scientific Achievements of the Spacelab Program: An Overview of the Missions," AIAA 94-4646, AIAA Space Programs and Technologies Conference, September 27–29, 1994 (NASA Goddard Library Electronic Database).

It was flown only in conjunction with the core segment. The modules were designed for a lifetime of 50 missions.[60]

End cones were bolted to both ends of the cylindrical laboratory segments. The truncated cones were 30.8 inches (78.2 centimeters) long; the large end was 161.9 inches (411.2 centimeters) in outside diameter and the small end was 51.2 inches (130 centimeters) in outside diameter. Each cone had three 16.4-inch (41.7-centimeter)-diameter cutouts, two located at the bottom of the cone and one at the top. Feedthrough plates for routing utility cables and lines could be installed in the lower cutouts of both end cones.

The ceiling skin panel of each segment contained a 51.2-inch (130-centimeter)-diameter opening for mounting a viewport adapter assembly. If the assembly was not used, the bolted-down cover plates closed the openings. The Spacelab viewport assembly could be installed in the upper cutout of the aft end cone, and the upper cutout of the forward end cone was for the pressurized module vent and relief valves.

Spacelab pallets were platforms designed for large instruments, experiments requiring direct exposure to space, and systems needing unobstructed or broad fields of view. Experiments could be mounted on the pallets or smaller special support structures if the instruments required exposure to space. For pallet-only missions, the support utilities for the instruments mounted on the pallet were housed in the Spacelab igloo, a temperature-controlled housing providing connections for data gathering, communications, electrical power, and cooling equipment. Vertically attached to the forward end of the first pallet, the igloo was 7.9 feet (2.4 meters) high and 3.6 feet (1.1 meters) in diameter.[61]

Because of the orbiter's center-of-gravity requirements, the Spacelab module had to be installed at the rear end of the orbiter payload bay. Equipment and crew passed through a pressurized tunnel between the crew compartment and the module. The tunnel was cylindrical with an internal unobstructed diameter of 40 inches (101.7 centimeters) and assembled in sections to allow length adjustment for different module configurations. Tunnel lengths of 18.88 feet (5.8 meters) and of 8.72 feet (2.7 meters) could be used. A "joggle" section of the tunnel compensated for the 42.1-inch (1.7-centimeter) vertical offset of the middeck airlock to the module's centerline. There were flexible sections on each end of the tunnel near the orbiter and Spacelab interfaces.

The airlock, tunnel adapter, tunnel, and module were at ambient pressure before launch. The tunnel adapter permitted crew members outfitted for extravehicular activity (EVA) to transfer from the middeck airlock to the payload bay without depressurizing the orbiter crew compartment and module. If an EVA was required, no crew members were permitted in the Spacelab tunnel or module.

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[60] "Spacelab Module," *http://liftoff.msfc.nasa.gov/Shuttle/spacelab/sl-elements.html* (accessed December 12, 2005).

[61] "Igloo," *http://liftoff.msfc.nasa.gov/Shuttle/spacelab/element-igloo.html* (accessed December 13, 2005).

Some Spacelab mission research required instruments to be pointed with very high accuracy and stability at stars, the Sun, Earth, or other targets of observation. The instrument pointing system provided precision pointing for instruments of diverse sizes and weights up to 15,432 pounds (7,000 kilograms) and could point them to within 2 arc seconds and hold them on target to within 1.2 arc seconds. The system consisted of a three-axis gimbal system mounted on a gimbal support structure and a control system. The control system was based on the inertial reference of a three-axis gyro package and operated by a gimbal-mounted mini-computer.

The Spacelab command and data management system (CDMS) provided a variety of services to Spacelab experiments and subsystems. Most of the CDMS commands were carried out using the computerized system aboard Spacelab, called the data processing assembly (DPA). The DPA formatted telemetry data and transferred the information to the orbiter for transmission, received command data from the orbiter and distributed it to Spacelab subsystems, transferred data from the orbiter to experiments, and distributed timing signals from the orbiter to experiments.[62]

The first Spacelab mission flew in 1983, the last on STS-90 in 1998. The program ended because the experiments performed on Spacelab could now be performed on the Space Station. Table 3–48 lists Spacelab missions from 1989 to 1998.

SPACEHAB

During the 1980s, as directed by legislation and national space policy, the commercial development of space became one of NASA's chief objectives. In the late 1980s, NASA's Office of Commercial Programs identified a significant number of payloads to further this objective, which required a sufficient level of flight activity for their support. In September 1989, a NASA analysis concluded that planned Space Shuttle flights did not offer adequate middeck-class accommodations for these payloads.

In February 1990, NASA initiated the Commercial Middeck Augmentation Module (CMAM) procurement through Johnson Space Center to provide support for these payloads. In November 1990, NASA awarded a five-year contract to SPACEHAB, Inc., of Arlington, Virginia, for the lease of their pressurized modules, the SPACEHAB Space Research Laboratories, to provide additional space by extending the Shuttle orbiter middeck into the Shuttle cargo bay for "crew-tended" payloads. This five-year lease arrangement covered several Shuttle flights and required SPACEHAB, Inc., to provide for the physical and operational integration of the SPACEHAB laboratories into the Space Shuttle orbiters, including experiment and integration services such as safety documentation and crew training.[63]

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[62] *Shuttle Crew Operations Manual,* pp. 2.25-1, 2.25-3, 2.25-5, 2.25-10, and 2.25-18.

SPACEHAB contracted with McDonnell Douglas's Huntsville Space Division in Alabama to provide the design, development, and physical integration of two space research laboratories. SPACEHAB also contracted with Alenia Aerospazio of Turin, Italy, to build the laboratories and design and build their passive thermal control systems.[64] These aluminum space research laboratory modules carried commercial and other attached payloads on the Shuttle and were used for *Mir* logistics flights. SPACEHAB unveiled its first module in May 1992; it flew on its first mission, STS-57, in 1993. Table 3–49 lists Shuttle SPACEHAB flights.

The SPACEHAB pressurized laboratory augmented Space Shuttle middeck experiment accommodations and provided Shuttle crew with a place to carry out experiments. It was located in the forward end of the Shuttle orbiter cargo bay and was accessed from the orbiter middeck through a tunnel adapter connected to an airlock. The module contained cooling, power and command, and data provisions in addition to SPACEHAB housekeeping systems (power distribution and control; lighting; fire and smoke detection; fire suppression; atmosphere control; status monitoring and control; and thermal control).

A single module weighed 9,628 pounds (4,367 kilograms), was 9.2 feet (2.8 meters) long, 11.2 feet (3.4 meters) high, and 13.5 feet (4.1 feet) in diameter. It increased pressurized experiment space in the Shuttle orbiter by 1,100 cubic feet (31 cubic meters), quadrupling the working and storage volume available. Environmental control of the laboratory's interior maintained ambient temperatures between 65°F and 80°F (18°C and 27°C) and had a total payload capacity of 3,000 pounds (1,361 kilograms).

The SPACEHAB laboratory could be configured with middeck-type lockers, racks, and/or a logistics transportation system to accommodate a variety of experiments and equipment. It could accommodate up to two SPACEHAB racks, either of which could be a "double rack" or "single rack" configuration. A double rack provided a maximum capacity of 1,250 pounds (567 kilograms) and 45 cubic feet (1.3 cubic meters) of volume, whereas a single rack provided half that capacity. The double-rack was similar in size and design to the racks planned for use in the Space Station.[65] Figure 3–19 shows the dimensions and arrangement of typical SPACEHAB interior configurations.

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[63] "Space Shuttle Mission STS-57 Press Kit," June 1993, p. 16, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_056_STS-057_Press_Kit.pdf* (accessed December 2, 2005).

[64] E-mail from Kimberly Campbell, Vice President Corporate Marketing and Communications, SPACEHAB, Inc., December 13, 2005.

[65] "Space Shuttle Mission STS-57 Press Kit," June 1993, pp. 16–17, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_056_STS-057_Press_Kit.pdf* (accessed December 2, 2005).

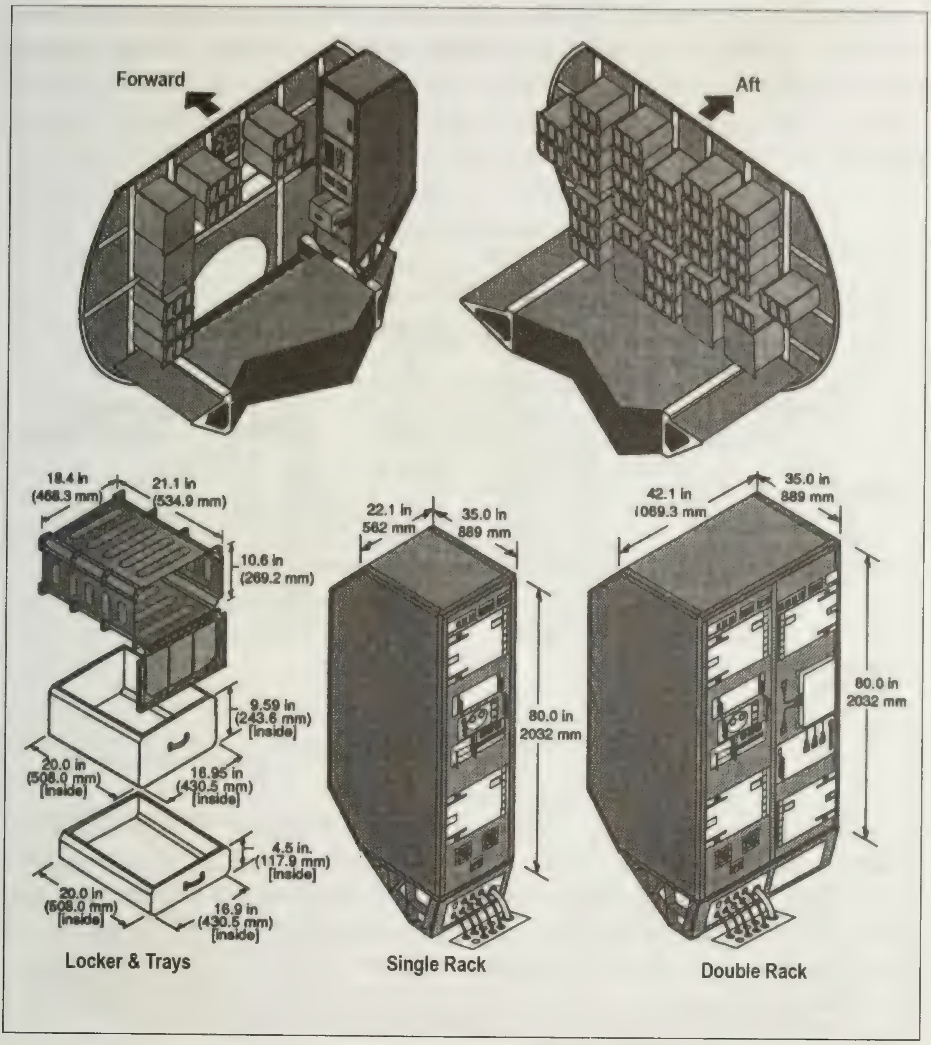
Forward
Aft
18.4 in
(468.3 mm)
21.1 in
(534.9 mm)
10.6 in
(269.2 mm)
9.59 in
(243.6 mm)
[inside]
20.0 in
(508.0 mm)
[inside]
16.95 in
(430.5 mm)
[inside]
4.5 in.
(117.9 mm)
[inside]
20.0 in
(508.0 mm)
[inside]
16.9 in
(430.5 mm)
[inside]
Locker & Trays
22.1 in
562 mm
35.0 in
889 mm
80.0 in
2032 mm
Single Rack
42.1 in
1069.3 mm
35.0 in
889 mm
80.0 in
2032 mm
Double Rack

Figure 3–19. Typical SPACEHAB Interior Configurations.

SPACEHAB offered three module configurations to accommodate specific mission requirements. Configuration 1 was connected to the orbiter using a modified Spacelab tunnel adapter and standard orbiter payload support resources from the cabin and payload bay (see Figure 3–20). The SPACEHAB single module-to-orbiter tunnel adapter connection used the Spacelab tunnel adapter, the SPACEHAB transition section, and the Spacelab flex section.

Configuration 2 allowed the SPACEHAB single module to be mounted in a new trunnion location to accommodate the orbiter docking system (ODS). The module was connected to the ODS using a Spacelab flex section, the new Spacelab extension for *Mir*, the SPACEHAB long tunnel segment, the SPACEHAB tunnel segment, and another flex section. All SPACEHAB module subsystems remained the same as in Configuration 1 except for a lower air exchange rate with the orbiter and the addition of two negative pressure relief valves.

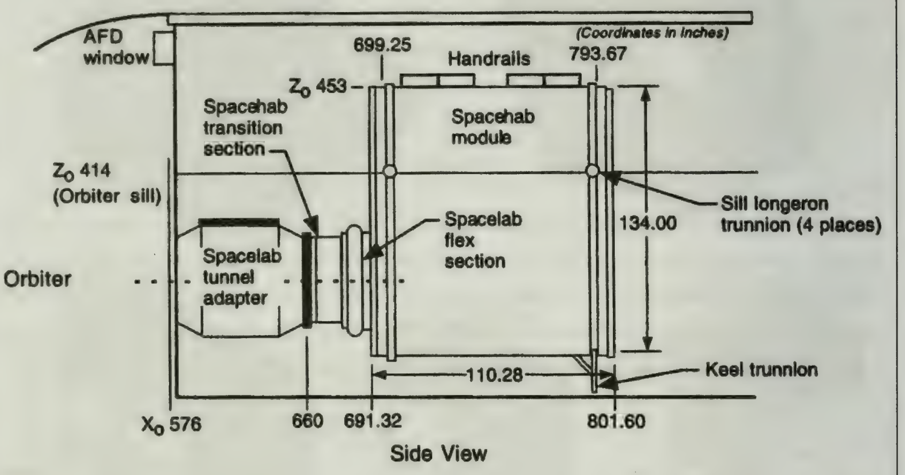
AFD window
(Coordinates in inches)
699.25
Handrails
793.67
Z_o 453
Spacehab transition section
Spacehab module
Z_o 414 (Orbiter sill)
Sill longeron trunnion (4 places)
Spacelab flex section
134.00
Orbiter
Spacelab tunnel adapter
110.28
Keel trunnion
X_o 576
660
691.32
801.60
Side View

Figure 3–20. SPACEHAB Configuration 1.

Configuration 3 was a double module consisting of one SPACEHAB module and one SPACEHAB module shell joined by an intermediate adapter (see Figure 3–21). This configuration had the same tunnel arrangement and attach points as Configuration 2, except for two trunnions moved farther back to accommodate the additional module. All SPACEHAB module subsystems remained the same as in Configuration 2 except for the addition of a fan and lights in the aft module segment.[66]

Animals in Space

Animals were a valuable part of space life sciences research and flew in space since the earliest days of the space program. All animal experiments aboard the Space Shuttle were housed either in the middeck area or in a laboratory research module specifically configured for the cargo bay. Two types of enclosures were flight-certified for use with on-board animals. Rodent experiments were usually carried in middeck lockers configured with animal enclosure modules that could be loaded onto the Shuttle 12 to 18 hours before launch and removed 3 to 6 hours after landing. Each module contained sufficient food for the duration of the mission and had an on-board water supply.

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[66] *Shuttle Crew Operations Manual,* pp. 2.24-1–2.24-2.

Animal enclosure modules could not be removed during a flight and were tightly sealed. Daily animal health checks were conducted during flights by opening the locker cover containing the module and pulling the module from its stowage position. The astronaut could observe the animals through the module's transparent cover. These modules were originally developed by General Dynamics for the Student Shuttle Flight Program.

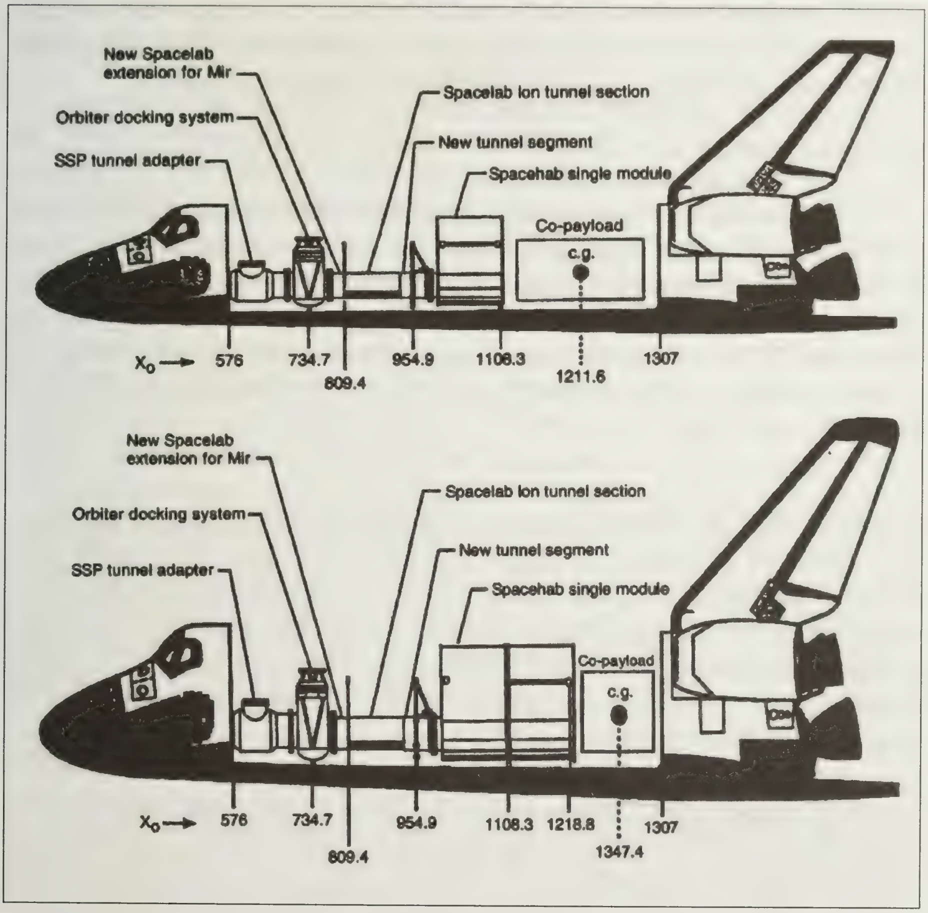
New Spacelab extension for Mir
Orbiter docking system
SSP tunnel adapter
Spacelab ion tunnel section
New tunnel segment
Spacehab single module
Co-payload
c.g.
X0
576
734.7
809.4
954.9
1108.3
1211.6
1307
New Spacelab extension for Mir
Orbiter docking system
SSP tunnel adapter
Spacelab ion tunnel section
New tunnel segment
Spacehab single module
Co-payload
c.g.
X0
576
734.7
809.4
954.9
1108.3
1218.8
1347.4
1307

Figure 3–21. SPACEHAB Configurations 2 (top) and 3.

The Spacelab module could be converted into an on-orbit research center providing additional space for rodents and primates. The Research Animal Holding Facility (RAHF) placed into a standard Spacelab double rack with housing space for up to 24 rats or four 1-kilogram (2.2-pound) squirrel monkeys. The facility provided environmental control, food, water, light, and waste management control for the animals. Unlike the sealed animal enclosure module, the animal cages could be removed from the RAHF and transported to a general purpose work area where the animal cages could be opened and the animals removed for tissue or fluid sample collection, administration of specific treatments, or euthanasia and tissue collection. Primates were used only for the Spacelab-3 mission in April 1985, and NASA did not plan to use primates again.[67]

In 1997, NASA issued a document titled "Principles for the Ethical Care and Use of Animals." The document stated three principles to guide the use of animals in research: to use the appropriate species and minimum number of animals required to obtain valid scientific results, to consider the potential societal good and overall ethical value whenever animals were used, and that the minimization of distress, pain, and suffering was a moral imperative.[68]

The Space Shuttle Crew[69]

NASA selects astronauts from a diverse pool of applicants with a wide variety of backgrounds. From the thousands of applications received, only a few are chosen for the intensive astronaut candidate training program.

The first group of astronaut candidates for the Space Shuttle program was chosen in 1978. In July of that year, 35 candidates began a rigorous training and evaluation period at Johnson Space Center to qualify for subsequent assignment for future Space Shuttle flight crews. This group of 20 mission scientist astronauts and 15 pilots completed training and went from astronaut candidate status to astronaut active status in August 1979. Six of the 35 were women and four were minorities. Through 1998, nine additional groups of pilots and mission specialists were added: 19 in 1980; 17 in 1984; 13 in 1985; 15 in 1987; 23 in 1990; 19 in 1992; 19 in 1995; 35 in 1996; and 25 in 1998. In addition, payload specialists, who were individuals other than NASA astronauts chosen to meet specialized requirements, completed the crews. Payload specialists could be from the United States or from other countries. International crew members are indicated in the mission tables that follow along with the agency or country that sponsored them.

Astronauts participating in the Russian Mir program received Russian language training before transferring to the Yuri Gagarin Cosmonaut Training Center for approximately 13 months. Russian language courses continued at the Gagarin Center until the astronaut reached the level required to begin technical training. Russian technical training included theoretical training on Russian vehicle design and systems, EVA training, scientific investigations and experiments, and biomedical training. Four weeks before the Shuttle launch that traveled to *Mir*, the astronaut returned to Johnson Space Center to train and integrate as part of the Shuttle crew.

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[67] Gary L. Borkowski, William W. Wilfinger, and Philip K. Lane, "Laboratory Animals in Science; Life Sciences Research," *Animal Welfare Information Center Newsletter* 6, no. 2-4 (Winter 1995/1996), *http://www.nal.usda.gov/awic/newsletters/v6n2/6n2borko.htm* (accessed November 22, 2005).

[68] "NASA Principles for the Ethical Care and Use of Animals," *http://grants.nih.gov/grants/olaw/references/dc97-2.htm* (accessed November 22, 2005). Also "Care and Use of Animals," NASA Policy Directive (NPD) 8910.1, Effective March 23, 1998 (canceled).

[69] *Astronaut Selection and Training*, Information Summaries, NP-1997-07-006 JSC, July 1997, *http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/np199707006jsc.pdf* (accessed July 10, 2005).

Commander/Pilot Astronauts

Pilot astronauts served as both Space Shuttle commanders and pilots. During flight, the commander had on-board responsibility for the vehicle, crew, mission success, and safety of the flight. The pilot assisted the commander in controlling and operating the vehicle and might assist in deploying and retrieving satellites using the remote manipulator system mechanical arm.

Mission Specialist Astronauts

Mission specialist astronauts worked with the commander and pilot, and the specialists had overall responsibility for coordinating Shuttle operations in the areas of Shuttle systems, crew activity planning, consumables usage, and experiment/payload operations. Mission specialists were trained in the details of the orbiter on-board systems, as well as the operational characteristics, mission requirements and objectives, and supporting equipment and systems for each of the experiments conducted on their assigned missions. Mission specialists performed EVAs, operated the remote manipulator system, and were responsible for payloads and specific experiment operations.

Payload Commander

The payload commander was an experienced mission specialist who had been designated to represent the NASA Flight Crew Operations Directorate and the Astronaut Office on a Spacelab or complex payload flight. This individual had full authority to work with the payload mission managers to identify and resolve issues associated with payload assignment and integration, training, crew member qualification, and operational constraints.[70]

Payload Specialists

Payload specialists were persons other than NASA astronauts (including foreign nationals) who had specialized on-board duties. They were career scientists or engineers selected by their employer or country for their expertise in conducting a specific experiment or commercial venture on a Space Shuttle mission.[71] They might be added to Shuttle crews if activities having unique requirements were involved and more than the minimum crew size of five were needed. First consideration for additional crew members was given to qualified NASA mission specialists. When payload specialists were required, they were nominated by NASA, the foreign sponsor, or the designated payload sponsor. In the case of NASA or NASA-related payloads, the nominations were based on the recommendations of the appropriate

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[70] *Shuttle Crew Operations Manual*, p. 2.25-1.

[71] Astronaut Fact Book, NASA Information Summaries, NP-2005-01-001 JSC, January 2005, *http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/astro.pdf* (accessed November 30, 2005).

Investigator Working Group. Although payload specialists were not part of the Astronaut Candidate Program, they were required to have the appropriate education and training related to the payload or experiment. All applicants must meet certain physical requirements and pass NASA space physical examinations with varying standards depending on classification.

Crew Services

Shuttle crew members provided services in three specific areas: EVAs, intravehicular activity, and in-flight maintenance. During EVAs, crew members donned pressurized spacesuits and life support systems, moved outside the protective environment of a spacecraft's pressurized cabin, and performed various payload-related activities in the microgravity environment of space, often outside the payload bay. The current spacesuit, designed for a total maximum duration of 7 hours, provided environmental protection, mobility, life support, and communications. Figure 3–22 shows the extravehicular mobility unit (EMU), or spacesuit.

There were three basic categories of EVA: scheduled, unscheduled, and contingency. A scheduled EVA was any EVA incorporated into the flight plan to complete a specific mission objective, for instance, repairing a satellite or testing equipment. (Figure 3–23 shows the EVA on the first Hubble Space Telescope servicing mission.) A quick-response EVA was a type of scheduled EVA that must be performed within a few hours after discovering a problem. It was usually associated with payload deployment. This type of EVA was prepared for and scheduled before the flight but might not be performed if the problem did not materialize. An unscheduled EVA was conducted to achieve payload operation success or to advance overall mission accomplishments. A contingency EVA was also unscheduled but was needed to ensure safe return of the orbiter and crew.

Even when an EVA was not scheduled, at least two crew members must be prepared to perform a contingency EVA if the situation made it necessary, for example: if payload bay doors failed to close properly and needed manual assistance or if equipment needed to be jettisoned from the orbiter. Beginning in 1998, EVAs were an important part of Space Station assembly. Earlier, U.S. astronauts had participated in spacewalks while on the Russian space station *Mir*. On April 29, 1997, Jerry Linenger became the first American to conduct a spacewalk from a foreign space station and in a non-American-made spacesuit in his 5-hour spacewalk.[72] Table 3–50 lists EVAs performed by U.S. Shuttle crews between 1989 and 1998.

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[72] "Linenger Increment: A Spacewalk and a Fire, History, Shuttle Flights and *Mir* Increments," *http://spaceflight1.nasa.gov/history/shuttle-Mir/history/h-f-linenger.htm* (accessed July 5, 2005).

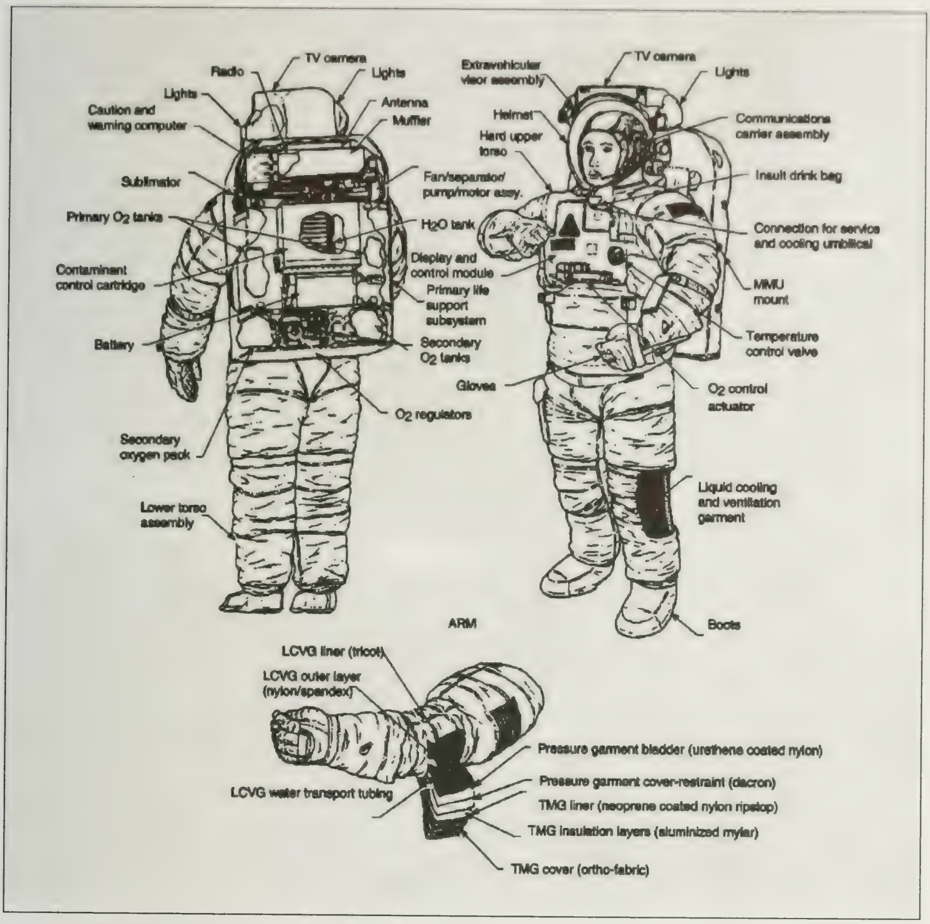
TV camera
Radio
Lights
Lights
Caution and warning computer
Antenna
Muffler
Sublimator
Fan/separator/ pump/motor assy.
Primary O_2 tanks
H_2O tank
Contaminant control cartridge
Display and control module
Primary life support subsystem
Battery
Secondary O_2 tanks
O_2 regulators
Secondary oxygen pack
Lower torso assembly
Extravehicular visor assembly
TV camera
Lights
Helmet
Hard upper torso
Communications carrier assembly
Insuit drink bag
Connection for service and cooling umbilical
MMU mount
Temperature control valve
Gloves
O_2 control actuator
Liquid cooling and ventilation garment
Boots
ARM
LCVG liner (tricot)
LCVG outer layer (nylon/spandex)
Pressure garment bladder (urethane coated nylon)
Pressure garment cover-restraint (dacron)
LCVG water transport tubing
TMG liner (neoprene coated nylon ripstop)
TMG insulation layers (aluminized mylar)
TMG cover (ortho-fabric)

Figure 3–22. Extravehicular Mobility Unit (Spacesuit).[73]

Intravehicular activity (IVA) included crew activities occurring within the orbiter crew compartment or a customer-provided pressurized module such as an attached pressurized module in the payload bay or a free flying module docked with the orbiter. IVA operations included module activation/deactivation, on-orbit operations, and monitoring while hatches were open, allowing free access to the orbiter. Normal operations included IVA activity (other than in-flight maintenance) planned before launch and listed in the mission timeline such as unpacking, assembly, and powering up. Off-nominal operations included performance of backup, malfunction, contingency, or emergency procedures not involving hardware modification or repair. IVA also included all activities in which crew members dressed in spacesuits and using life support systems performed hands-on operations inside a customer-supplied crew module.[74]

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[73] *Shuttle Crew Operations Manual*, p. 2.11-2.

[74] "Mission Preparation and Prelaunch Operations," *NSTS Shuttle Reference Manual* (1988), *http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/stsover-prep.html#stsover-crewserv* (accessed November 12, 2005).

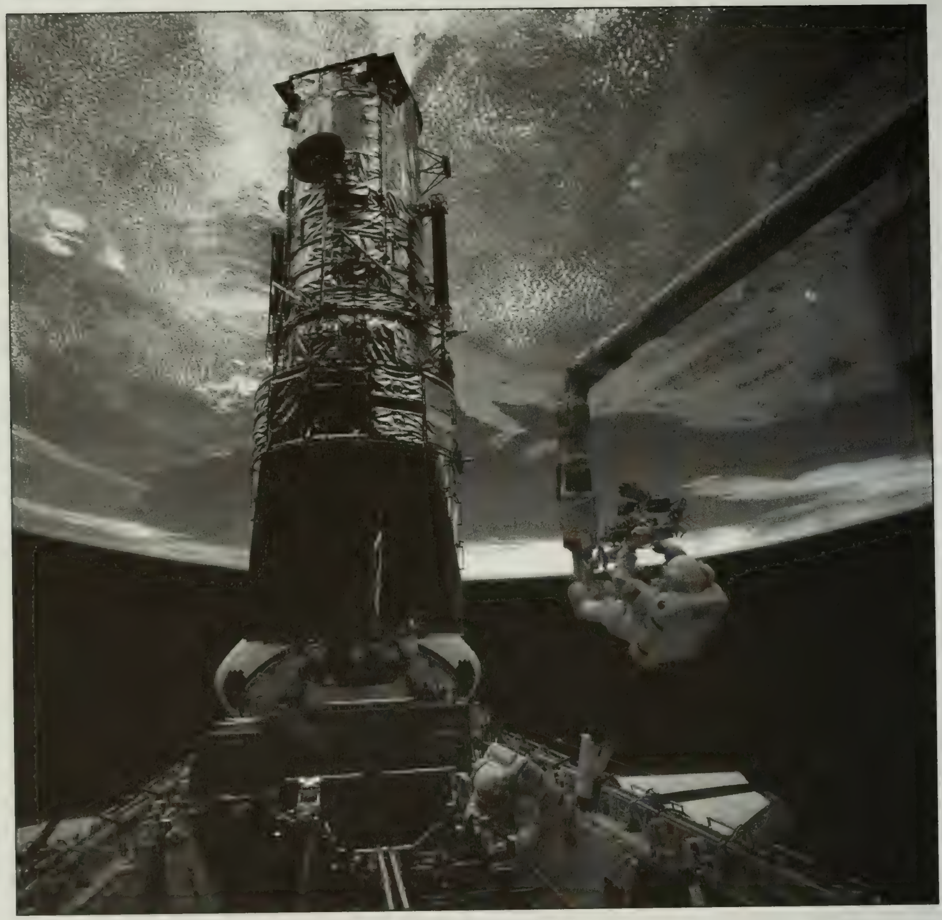

Figure 3–23. Astronaut F. Story Musgrave is seen anchored on the end of the Remote Manipulator System Arm as he prepares to be elevated to the top of the Hubble Space Telescope to install protective covers on the magnetometers, December 9, 1993. (NASA Photo No. GPN-2000-001085)

In-flight maintenance was any abnormal on-orbit maintenance or repair of a malfunctioning payload conducted by the crew within a pressurized vessel or payload module to keep the payload operable or to return it to operability. In-flight maintenance normally involved removal of payload panels, mating and demating of electrical connectors, or replacement of line replaceable units.[75]

Space Shuttle Abort Modes

Space Shuttle launch abort philosophy is aimed toward safe and intact recovery of the flight crew, orbiter, and its payload. A Shuttle launch scrub or abort might occur up to solid rocket booster ignition. Normally, launch scrubs before SSME start were followed by an orderly safing procedure and crew egress, assisted by the closeout crew. A fully fueled Shuttle on the launch pad might present an extremely hazardous situation if toxic vapors, fire, or structural damage were present. A launch abort after SSME start was automatically controlled by the ground launch sequencer. The presence of excess hydrogen was the most serious hazard, resulting in a very dangerous hydrogen fire invisible to the eye. This situation occurred during a launch attempt for STS-41-D in 1984.

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[75] *Space Shuttle Systems Payload Accommodations*, NSTS 07700, Volume XIV, Appendix 9. "System Description and Design Data–Intravehicular Activities," pp. 1-1, 1-2, *http://shuttlepayloads.jsc.nasa.gov/data/PayloadDocs/documents/07700/App_09.pdf* (accessed November 15, 2005).

Should an abnormal event occur that terminated a flight or prelaunch operation and resulted in substantial damage to the Shuttle and/or injury to personnel, the NASA Test Director would declare a contingency situation. This would alert fire and rescue personnel and put in motion preplanned procedures to minimize further damage and injuries. The NASA Test Director might also initiate action if an emergency condition existed that required immediate action to prevent loss of life or destruction of equipment. In preparation for a potential emergency condition, a hazardous condition might be declared if there was a threat to personnel health or safety. A hazardous condition might develop into an emergency condition.

There were two basic types of ascent abort modes: intact and contingency. Intact aborts were designed to provide a safe return of the orbiter to a planned landing site. Contingency aborts were designed to permit crew survival following more severe failures when an intact abort was not possible. A contingency abort would usually result in a crew bailout.

- Abort-To-Orbit (ATO)—This mode would be chosen if partial loss of main engine thrust occurred late enough to permit reaching a minimal 105-nautical-mile (194.5-kilometer) orbit with orbital maneuvering system engines.
- Abort-Once-Around (AOA)—This mode would be chosen when there was earlier main engine shutdown with the capability to allow one orbit around Earth before landing at Edwards Air Force Base, California; White Sands Space Harbor (Northrup Strip), New Mexico; or the Shuttle Landing Facility at Kennedy Space Center, Florida.
- Transoceanic Abort Landing (TAL)—This mode would be selected when the loss of two main engines midway through powered flight would force a landing at Ben Guerir, Morocco; Moron, Spain; or Banjul, The Gambia.[76]
- Return-To-Launch-Site (RTLS)—This mode would be selected when there was early shutdown of one or more engines, and when there was not enough energy to reach Ben Guerir. It would result in a pitch around and thrust back toward Kennedy Space Center until the Shuttle was within gliding distance of the Shuttle Landing Facility.[77]

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[76] E-mail from Kyle Herring, NASA Public Affairs Office, Johnson Space Center, November 30, 2005.

[77] *Shuttle Crew Operations Manual*, pp. 6.1-1–6.1-2, 6.2-1.

Since Space Shuttle flights began through 1998, there have been very few aborts. The first on-pad abort-after-ignition occurred on STS-41-D in 1984. STS-51-F experienced both an on-pad abort and an abort-to-orbit during two launch attempts in July 1985. STS-55 experienced an on-pad abort-after-ignition on March 22, 1993, when SSME No. 3 failed to ignite completely.[78]

Space Shuttle Missions

Between 1989 and 1998, 66 Space Shuttle missions flew. The following section describes those missions, presented chronologically. Table 3–51 lists summary data. Tables 3–52 through 3–116 list Shuttle mission characteristics and events. Most mission information was obtained from online Shuttle chronologies and archives.[79] Additional material comes from the press kits for each mission, *U.S. Human Spaceflight* (NASA Monographs in Aerospace History No. 9), and specific pages from the National Space Science Data Center (NSSDC) Master Catalog.[80] Other sources are noted in footnotes beneath the text. Abbreviations relating to crew positions are: CDR–Commander; PLT–Pilot; MC–Mission Commander, MS–Mission Specialist, PC–Payload Commander, and PS–Payload Specialist.

The online Shuttle mission archives generally presented Shuttle altitudes as a single value. However, mission descriptions indicated that altitude often changed during a mission, sometimes for days at a time, to accomplish mission objectives. Unless the change in altitude was especially significant, only the single value presented in the mission archive is noted in the mission tables. The reader can find additional details relating to mission payloads in chapter 4 of this volume, Space Science, and in the next volume of the *NASA Historical Data Book*. Missions shown as "successful" mission were those in which mission objectives were achieved.

STS-29

This mission launched on March 13, 1989, from Kennedy Space Center and landed March 19 at Edwards Air Force Base. The primary payload was the Tracking and Data Relay Satellite-4 (TDRS-4) attached to an Inertial Upper Stage (IUS), which became the third TDRS deployed. After deployment, the IUS propelled the satellite to geosynchronous orbit. See Table 3–52 for further details.

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[78] Jenkins, pp. 272, 274, 304, 305.

[79] "Mission Chronologies," *http://www-pao.ksc.nasa.gov/kscpao/chron/chrontoc.htm* (accessed May–June 2005); "1999–2004 Shuttle Mission Archives," *http://www.nasa.gov/centers/kennedy/shuttleoperations/archives/1999-2004.html* (accessed May–June 2005).

[80] Judy A. Rumerman, compiler, *U.S. Human Spaceflight: A Record of Achievement, 1961–1998*, Monographs in Aerospace History, no. 9 (Washington, DC: NASA History Division, July 1998); "Space Shuttle Press Kits," *http://www.jsc.nasa.gov/history/shuttle_pk/shuttle_press.htm* (accessed May–June 2005); NSSDC Master Catalog, *http://nssdc.gsfc.nasa.gov/nmc/sc-query.html* (accessed June–December 2005).

STS-30

This mission launched on May 4, 1989, from Kennedy Space Center and landed May 8 at Edwards Air Force Base. The mission's primary payload was the Magellan/Venus Radar Mapper spacecraft with its attached IUS, which boosted the spacecraft on its proper trajectory for a 15-month journey to Venus. It was the first Shuttle launch of a deep space probe and the first U.S. planetary mission in 11 years. Secondary payloads were the Mesoscale Lightning Experiment (MLE), microgravity research with the Fluids Experiment Apparatus (FEA), and the AMOS experiment. One of the general purpose computers failed on orbit and had to be replaced. It was the first time such an operation was performed while orbiting. See Table 3–53 for further mission details.

STS-28

This classified DOD mission launched on August 8, 1989, from Kennedy Space Center and landed on August 13 at Edwards Air Force Base. See Table 3–54 for further mission details.

STS-34

This mission launched October 18, 1989, from Kennedy Space Center and landed October 23 at Edwards Air Force Base. The Galileo spacecraft was launched on the Shuttle's fifth orbit with a boost from its IUS toward Jupiter by way of Venus. It was the Shuttle's second interplanetary payload.

Also in the payload bay of *Atlantis* was the Shuttle Solar Backscatter Ultraviolet (SSBUV) instrument. The SSBUV provided calibration of backscatter ultraviolet instruments concurrently being flown on free-flying satellites. The SSBUV was contained in two canisters in the payload bay, one holding the SSBUV spectrometer and five supporting optical sensors and a second housing data, command, and power systems. An interconnecting cable provided the communication link between the two canisters. *Atlantis* also carried several secondary payloads involving radiation measurements, polymer morphology, lightning research, microgravity effects on plants, and a student experiment on ice crystal growth in zero gravity. See Table 3–55 for further mission details.

STS-33

This classified DOD mission launched November 22, 1989, from Kennedy Space Center and landed November 27 at Edwards Air Force Base. It was the first night launch since the return to flight. See Table 3–56 for further mission details.

STS-32

This mission launched January 9, 1990, from Kennedy Space Center and landed January 20 at Edwards Air Force Base. Lasting almost 11 days, STS-32 was the longest Shuttle flight to date.

The Long Duration Exposure Facility (LDEF), released into orbit on STS-41-C in 1984, was finally retrieved after nearly six years in space. LDEF was a 14.5-foot by 30-foot (4.4-meter by 9.1-meter) 12-sided array of more than 70 panels designed to obtain data important to designers of spacecraft on the effects of the orbital environment on metals, coatings, and other materials used in constructing spacecraft. It provided an STS-transported, low-cost, reusable, free-flying structure to carry many different science and technology experiments. The LDEF required little or no electric power and data processing while in long-duration spaceflight.

While in space, the LDEF completed 32,422 Earth orbits, allowing investigators to increase their scientific and technological understanding of the space environment and its effects. LDEF experienced one-half of a solar cycle, as it was deployed during a solar minimum and retrieved at a solar maximum. After rendezvousing with the large, cylindrical satellite—one of the most complicated space rendezvous operations ever—the Shuttle crew photographed the LDEF in orbit, grappled it with the remote manipulator system arm, and then stowed it in the cargo bay of *Columbia*. Scientists who examined the LDEF after landing found evidence of erosion and micrometeorite impacts, as expected. By the time LDEF was retrieved, its orbit altitude had decayed to ~175 nautical miles (324 kilometers), and the satellite was a little more than one month away from reentering Earth's atmosphere. Figure 3–24 shows the LDEF.

A SYNCOM DOD communications satellite also was deployed on the mission. See Table 3–57 for further mission details.

STS-36

This classified DOD mission launched February 28, 1990, from Kennedy Space Center and landed March 4 at Edwards Air Force Base. Launch was postponed several times (and then postponed further because of bad weather) because of the illness of the mission commander, John Creighton. The mission was the first time since the Apollo 13 mission in 1970 that a human spaceflight mission had been postponed because of the illness of a crew member.

This flight flew at an inclination orbit of 62 degrees, the highest inclination flown by the Shuttle to date. See Table 3–58 for further mission details.

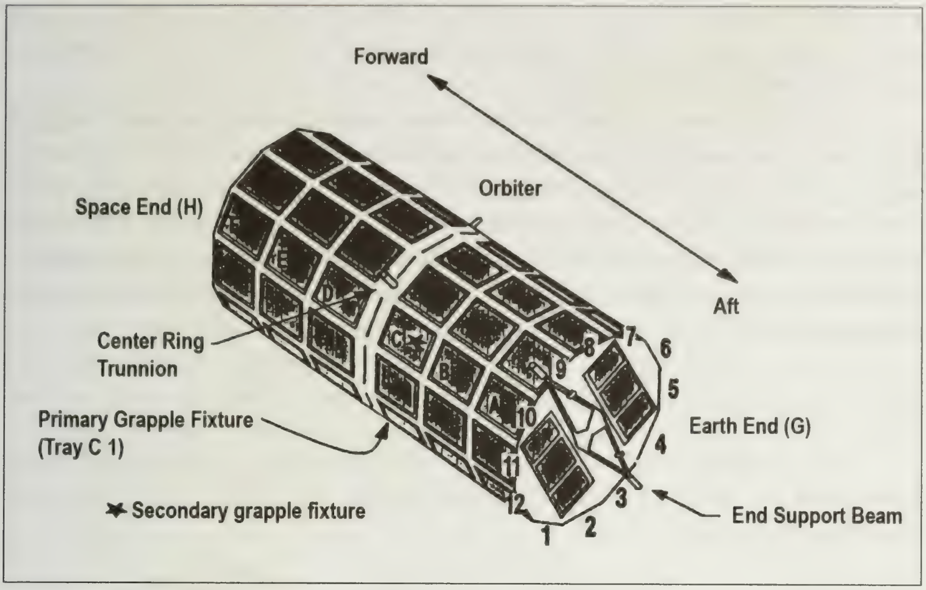

Figure 3–24. The LDEF was retrieved by STS-32 after nearly six years in space.

STS-31

This mission launched April 24, 1990, from Kennedy Space Center and landed April 29 at Edwards Air Force Base. The Hubble Space Telescope, first of the Great Observatories and first large optical telescope to be placed above Earth's atmosphere, was released into orbit by the remote manipulator system arm on the second day of the mission. Because of the need to place the telescope above most of Earth's atmosphere, *Discovery* flew the highest Shuttle orbit to date, reaching an altitude of slightly more than 611 kilometers (330 nautical miles). After the telescope was deployed, the astronauts conducted experiments in crystal growth and monitored the radiation environment aboard the orbiter. See Table 3–59 for further mission details.

STS-41

This mission launched October 6, 1990, from Kennedy Space Center and landed October 10 at Edwards Air Force Base. It was the heaviest payload to date. The deployment of ESA's Ulysses to explore the polar regions of the Sun was the highlight of this four-day mission. Ulysses was released from *Discovery*'s cargo bay on the first day of the mission; on-board rockets were fired to send the spacecraft toward a gravity-assist at Jupiter to observe the polar regions of the Sun. For the first time, a PAM and IUS combined together were used to send the spacecraft into its trajectory. They replaced the canceled Centaur upper stage that had been planned for this mission. After Ulysses's deployment, the astronauts conducted a number of secondary experiments, including measuring atmospheric ozone, studying the effects of atomic oxygen on spacecraft materials, and evaluating a new "hands-off" voice command system in the Shuttle crew cabin.

Also in *Discovery*'s payload bay was the Airborne Electrical Support Equipment, an electrical generating system mounted on the side of the bay to supply power to Ulysses. The INTELSAT Solar Array Coupon, samples of solar array materials mounted on *Discovery*'s remote manipulator system, studied the effects of atomic oxygen wear on solar panels in preparation for a future Shuttle mission to rescue the stranded INTELSAT satellite. See Table 3–60 for further mission details.

STS-38

This classified DOD mission launched November 15, 1990, and landed November 20, 1990, at Kennedy Space Center. See Table 3–61 for further mission details.

STS-35

This mission launched December 2, 1990, from Kennedy Space Center and landed December 10 at Edwards Air Force Base. This mission was the first Shuttle flight dedicated to a single discipline: astrophysics. Using Spacelab pallets with the instrument pointing system and igloo, *Discovery* carried a group of astronomical telescopes called Astro-1 in its cargo bay. The crew included four individuals with doctorates in astronomy: Jeffrey Hoffman, Robert Parker, Samuel Durrance, and Ronald Parise. Despite several hardware malfunctions, the crew observed a wide variety of astronomical targets, from comets to quasars, with particular attention to x-ray and ultraviolet wavelengths. See Table 3–62 for further mission details.

STS-37

This mission launched April 5, 1991, from Kennedy Space Center and landed April 11 at Edwards Air Force Base. The initial landing at Edwards was waved off and rescheduled for the next day at Kennedy. That, too, was waved off because of fog, and the mission landed one orbit later at Edwards.

The Gamma Ray Observatory, the second "Great Observatory," was released by the Shuttle's remote manipulator system arm on the third day of the flight, after astronauts Jerry Ross and Jay Apt made an unscheduled spacewalk to repair an antenna on the spacecraft. The Gamma Ray Observatory was the heaviest science satellite ever launched from the Shuttle (see Figure 3–25).

Later in the mission, Ross and Apt returned to the cargo bay to test Crew and Equipment Translation Aids, rail-mounted mechanical pushcarts planned for use on Space Station *Freedom*. The two spacewalks were the first in more than five years. See Table 3–63 for further mission details.

STS-39

This mission launched April 28 and landed May 6, 1991, at Kennedy Space Center. This was the first unclassified defense-related mission of the Shuttle program. Highlighted by around-the-clock observations, it included experiments sponsored by the U.S. Air Force and the Strategic Defense Initiative Organization. The studies included extensive infrared, ultraviolet, visible, and x-ray observations of the space environment and the Shuttle itself. On-board instruments also returned high-quality images of Earth's aurora. In an experiment related to ballistic missile defense, *Discovery* released a Shuttle Pallet Satellite (SPAS) instrument platform equipped with infrared sensors to fly in formation and observe rocket thruster plumes while the Shuttle performed a complicated series of maneuvers. The satellite was retrieved and returned to Earth at the end of the mission. See Table 3–64 for further mission details.

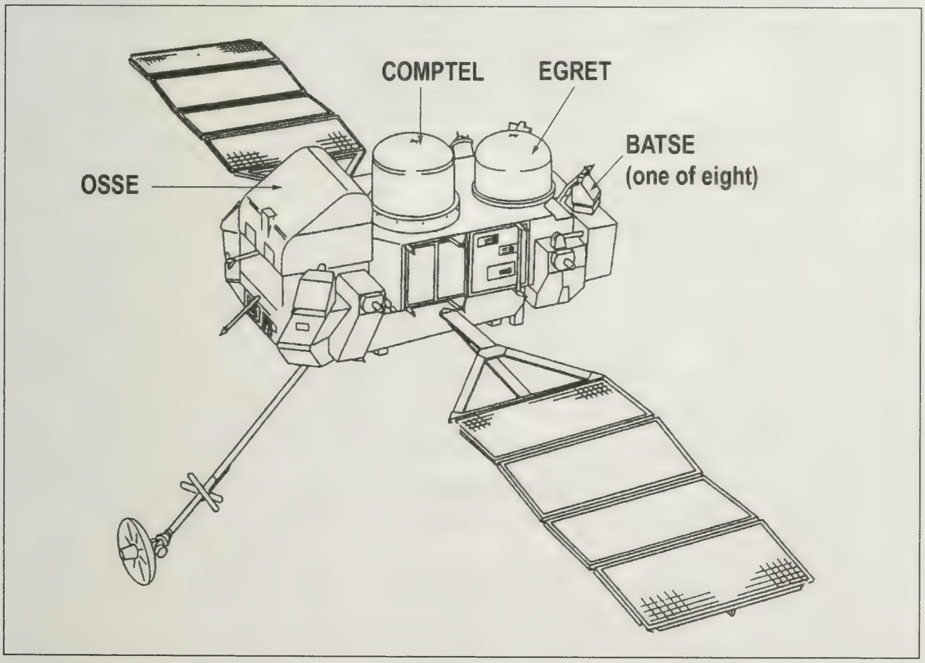

Figure 3–25. The Gamma Ray Observatory, the second "Great Observatory," was the most massive instrument ever launched by the Space Shuttle to date.

STS-40

This mission launched on June 5, 1991, from Kennedy Space Center and landed June 14 at Edwards Air Force Base. The SLS-1 mission was the first mission dedicated entirely to understanding the physiological effects of spaceflight. The crew conducted an extensive series of biomedical experiments during the nine-day mission, and the results were compared with baseline data collected on the ground before and after the flight. In addition to the human subjects, rodents and jellyfish were aboard to test their adaptation to microgravity. See Table 3–65 for further mission details.

STS-43

This mission launched August 2, 1991, and landed August 11, 1991, at Kennedy Space Center. It marked the first scheduled landing at Kennedy's Shuttle Landing Facility since January 1986. The primary payload, the TDRS-5, attached to an IUS, was deployed about 6 hours into flight. The IUS propelled the satellite into geosynchronous orbit as TDRS-5 became the fourth member of the orbiting TDRS cluster. See Table 3–66 for further mission details.

STS-48

This mission launched September 12, 1991, from Kennedy Space Center and landed September 18 at Edwards Air Force Base. The UARS was deployed on the third day of the mission. The 14,500-pound (6,577-kilogram) observatory conducted the most extensive study to date of the upper atmosphere as it investigated the stratosphere, mesosphere, and lower thermosphere. See Table 3–67 for further mission details.

STS-44

This mission launched November 24, 1991, from Kennedy Space Center and landed December 1, 1991, at Edwards Air Force Base. The mission was shortened by three days because one of the orbiter's three inertial measurement units failed.

The unclassified DOD payload included the Defense Support Program (DSP) early warning satellite and attached IUS, which was deployed on the first day of the mission. On-board payloads focused on contamination experiments and medical research. See Table 3–68 for further mission details.

STS-42

This mission launched January 22, 1992, from Kennedy Space Center and landed January 30 at Edwards Air Force Base. The primary payload was the International Microgravity Laboratory-1 (IML-1) using the Spacelab long module. The IML-1 mission was the first in a series of international Shuttle flights dedicated to fundamental life and microgravity sciences research. IML-1 science operations were a cooperative effort between the *Discovery*'s crew in orbit and mission management, scientists, and engineers in a control facility at Marshall Space Flight Center. Though the crew and the ground-based controllers and science teams were separated by many miles, they interacted in much the same way as they would if working side by side. The mission was extended by one day to continue mission work. Figure 3–26 shows STS-42 astronauts in the IML-1 science module.

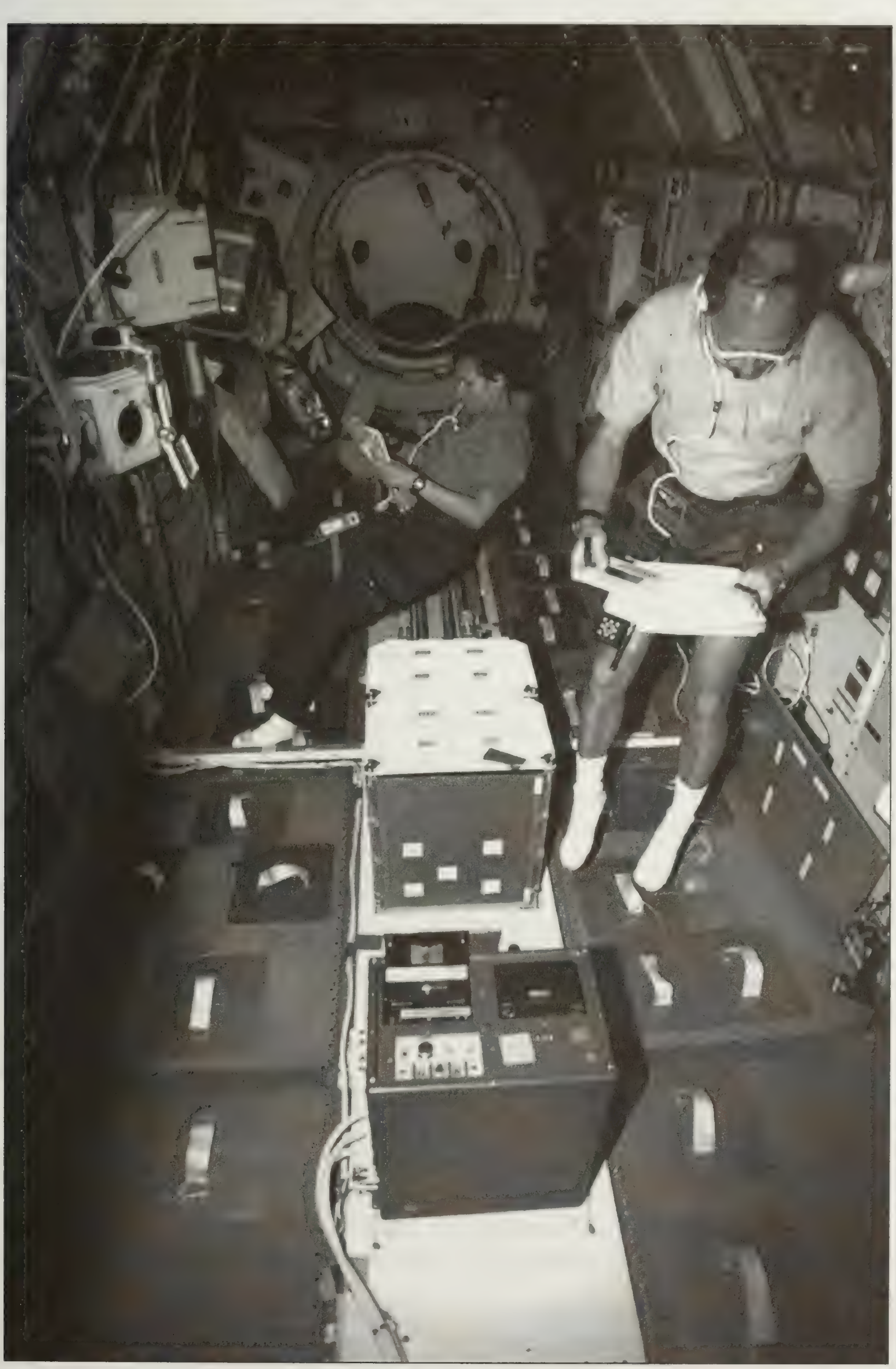

Figure 3–26. Bondar and Thagard work with experiments in the IML-1 Science Module. The two, along with four other NASA astronauts and a second IML-1 payload specialist, spent more than eight days conducting experiments in Earth orbit. Part of the SAMS is in the center foreground. (NASA-MSFC Photo MSFC-9250420)

Other payloads included 12 GAS canisters, a number of middeck payloads, and two SSIP experiments. See Table 3–69 for further details.

STS-45

This mission launched March 24, 1992, and landed April 2 at Kennedy Space Center. It marked the first flight of the ATLAS-1, which was mounted on Spacelab pallets in the orbiter's cargo bay. An international team consisting of the United States, France, Germany, Belgium, the United Kingdom, Switzerland, the Netherlands, and Japan provided 12 instruments performing 13 investigations in atmospheric chemistry, solar radiation, space plasma physics, and ultraviolet astronomy. The ATLAS-1 was co-manifested with the SSBUV, which provided highly calibrated measurements of ozone to fine-tune measurements made by other NASA and NOAA satellites. The mission was extended one day to continue investigations. Figure 3–27 shows the payload configuration. See Table 3–70 for further mission details.

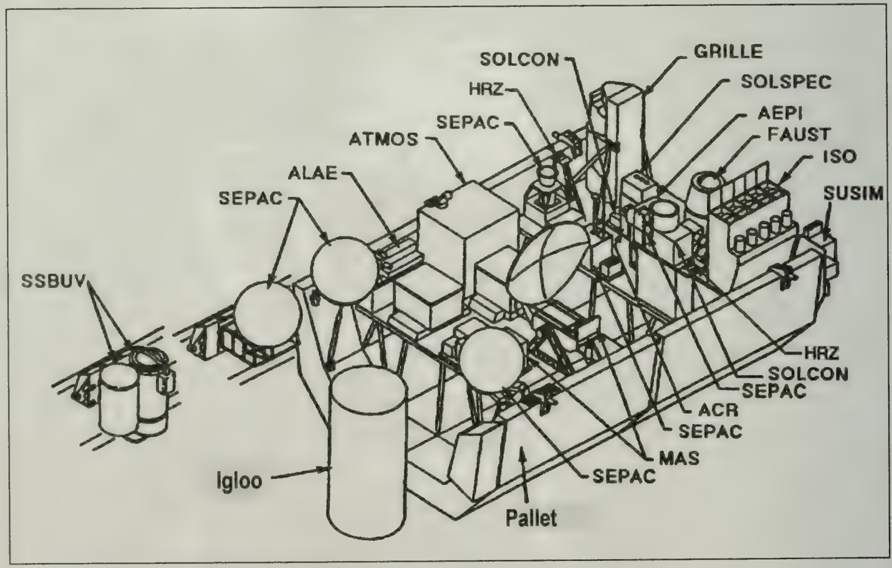

Figure 3–27. ATLAS-1 Payload Configuration.

STS-49

This mission launched May 7, 1992, from Kennedy Space Center and landed May 16 at Edwards Air Force Base. During a mission that was extended by two days, the crew successfully captured and redeployed the INTELSAT VI satellite, which had been in an unusable orbit since the upper stage failed to separate from the second stage of its Titan launch vehicle in

March 1990. Capture of the satellite required three spacewalks and the simultaneous efforts of three spacewalking astronauts as well as the maneuvering skill of the Shuttle commander.

The mission was marked by a number of "firsts." Four spacewalks, the most ever on a single mission, highlighted the first flight of the orbiter *Endeavour*. Two of these were the longest in U.S. spaceflight history to date, the first lasting 8 hours, 29 minutes and the second 7 hours, 45 minutes. The flight also featured the longest spacewalk to date by a female astronaut and was the first spaceflight in which three crew members worked outside the spacecraft at the same time. It also was the first time that astronauts attached a live rocket motor to an orbiting satellite, when they attached a perigee kick motor to the INTELSAT VI satellite, which later boosted it into its proper orbit. This was the first Shuttle mission requiring three astronauts to rendezvous with an orbiting spacecraft.

The crew also practiced assembly techniques for the planned Space Station *Freedom* and tested the new drag chute after orbiter nosegear touchdown at Edwards Air Force Base. See Table 3–71 for further details.

STS-50

This mission launched June 25 and landed July 9, 1992, at Kennedy Space Center. It marked the first use of the Extended Duration Orbiter kit, tanks of liquid oxygen and hydrogen mounted in the payload bay to extend the energy-generating fuel cell's capacity, allowing mission duration to surpass all previous U.S. crewed spaceflights to date with the exception of the three Skylab missions in 1973–1974. The USML-1 made its first flight on this mission. It was the first in a planned series of flights to advance microgravity research efforts in several disciplines. See Table 3–72 for further mission details.

STS-46

This mission launched July 31 and landed August 8, 1992, at Kennedy Space Center. The primary mission objective was the deployment of the ESA's EURECA and the operation of the NASA-Italian TSS, with Italian astronaut Franco Malerba on board the Shuttle. EURECA was the largest satellite produced in Europe. It carried 15 major science experiments, mostly in microgravity sciences.[81] After a delay and a shorter than planned thruster firing, the satellite was successfully boosted to operational orbit.

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[81] Jenkins, p. 301.

During TSS deployment, the satellite at the end of the tether reached a distance of only 840 feet (256 meters), rather than its planned 12.5 miles (20.1 kilometers) because of a jammed tether line.[82] After additional unsuccessful attempts to free the tether, the satellite was restowed for return to Earth. Figure 3–28 shows the TSS viewed from the orbiter *Atlantis*. See Table 3–73 for further mission details.

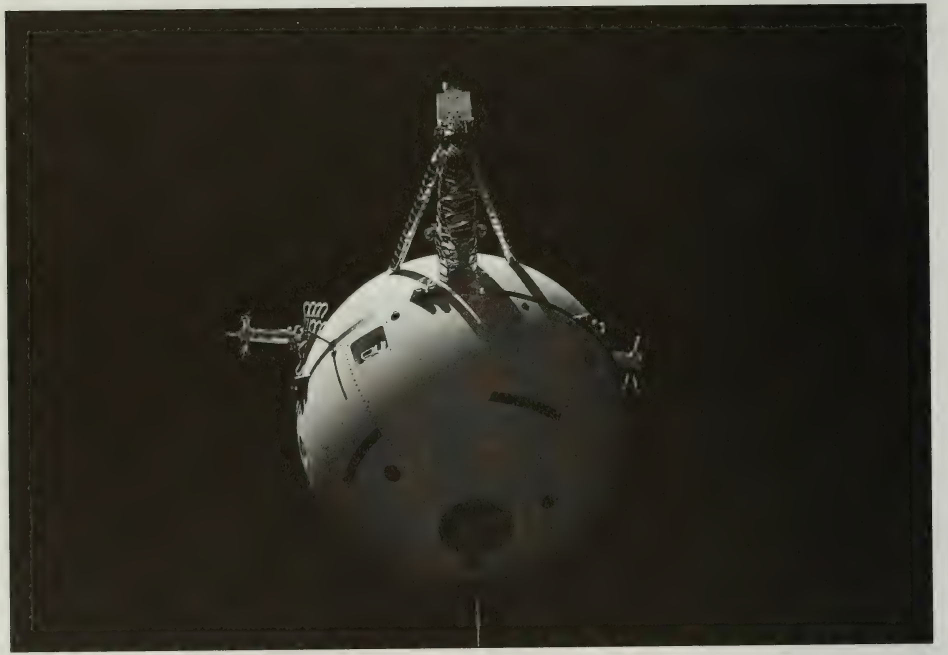

Figure 3–28. This Space Shuttle Orbiter Atlantis *(STS-46) on-board photo is a close-up view of the TSS-1 deployment. (NASA-MSFC Photo No. MSFC-9410850)*

STS-47

This mission launched September 12 and landed September 20, 1992, at Kennedy Space Center. It was the first on-time launch since STS-61-B in 1985. Spacelab-J, the first Japanese Spacelab, flew on this flight. The crew included the first African-American woman to fly in space, the first married couple to fly on the same mission, and the first Japanese person to fly on the Space Shuttle. This mission marked the first operational use of the new drag chute, which was deployed before nosegear touchdown. See Table 3–74 for further mission details.

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[82] Distance of 840 feet (256 meters) of tether deployment was stated in the "STS-46 Mission Chronology," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-46.htm* (accessed July 6, 2005); The summary of the Investigative Board corroborated that figure, "Report Details Causes of Tethered Satellite Malfunctions," *NASA News* Release 92-196, November 6, 1992, *http://nssdc.gsfc.nasa.gov/space/text/tss-summary.txt* (accessed December 4, 2005); Jenkins, p. 301, and the "STS-46 Mission Archives" at *http://science.ksc.nasa.gov/shuttle/missions/sts-46/mission-sts-46.html* (accessed December 4, 2005), stated the distance as 860 feet (262 meters).

STS-52

This mission launched October 22 and landed November 1, 1992, at Kennedy Space Center. It deployed the Laser Geodynamic Satellite II (LAGEOS), a joint effort of NASA and the Italian Space Agency. This dense 0.6-meter (2-foot)-diameter sphere was covered by retroflectors to allow study of dynamic motions of Earth's crust using precise laser tracking of the satellite from ground stations around the world. LAGEOS II was deployed on flight day two and boosted into an initial elliptical orbit by the IRIS, flying for the first time. The apogee kick motor later fired to adjust the spacecraft's orbit at an operational altitude of 5,616 kilometers by 5,905 kilometers (3,490 miles by 3,669 miles).[83]

The mission also carried USMP-1, which was activated on the first day of the flight. On-board studies focused on the influence of gravity on basic fluid and solidification processes. See Table 3–75 for further mission details.

STS-53

This mission launched December 2, 1992, from Kennedy Space Center and landed December 9 at Edwards Air Force Base. It was the first flight of *Discovery* after its OMDP. This was the last Shuttle flight for the DOD. *Discovery* deployed a classified payload followed by unclassified flight activities. GAS hardware located in the cargo bay or on the middeck contained or were attached to 10 secondary payloads. See Table 3–76 for further mission details.

STS-54

This mission launched January 13 and landed January 19, 1993, at Kennedy Space Center. The fifth TDRS-6, part of NASA's orbiting communications system, was deployed about 6 hours after liftoff. Figure 3–29 shows the on-orbit configuration.

On the fifth day of the flight, astronauts Mario Runco and Gregory Harbaugh spent almost 5 hours working in the open payload bay, performing a series of EVA tasks to increase NASA's knowledge of working in space. The astronauts tested their abilities to move freely in the cargo bay, climb into foot restraints without using their hands, and simulated carrying large objects in a microgravity environment.

A Hitchhiker experiment, the Diffuse X-ray Spectrometer, collected data on x-ray radiation from stars and galactic gases. See Table 3–77 for further mission details.

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[83] E-mail from Carey Noll; data provided by LAGEOS science contact Peter Dunn, November 25, 2005.

STS-56

This mission launched April 9, 1993, and landed April 17, 1993, at Kennedy Space Center. The primary payload was the second ATLAS-2, a Spacelab pallet mission that was one element of NASA's Mission to Planet Earth program. The pallet in the payload bay held six instruments, and a seventh was mounted in two GAS canisters.

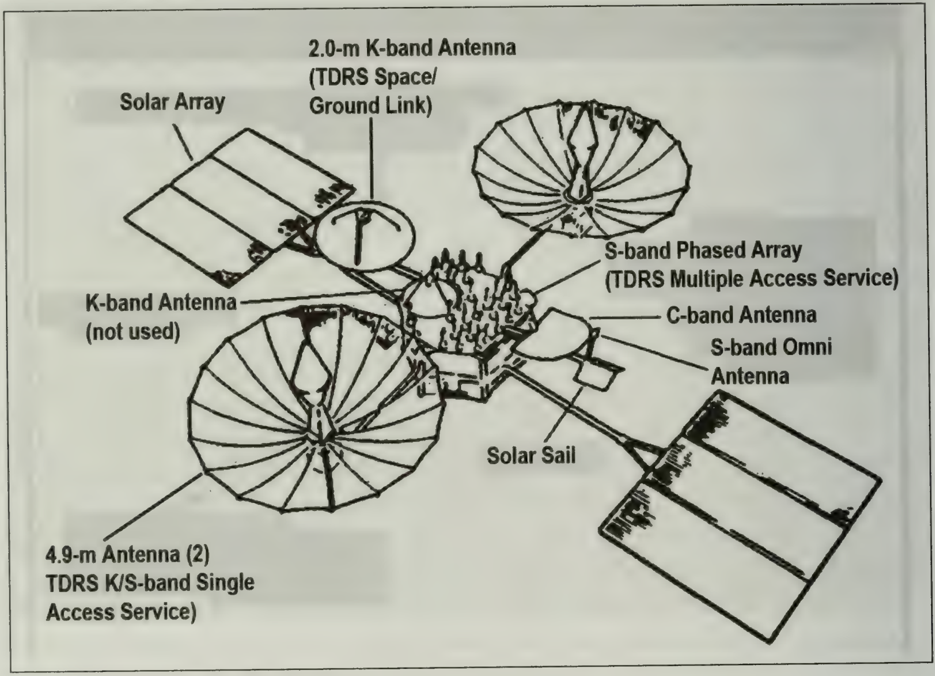
2.0-m K-band Antenna
(TDRS Space/
Ground Link)
Solar Array
S-band Phased Array
(TDRS Multiple Access Service)
K-band Antenna
(not used)
C-band Antenna
S-band Omni
Antenna
Solar Sail
4.9-m Antenna (2)
TDRS K/S-band Single
Access Service)

Figure 3–29. TDRS-F (6) On-Orbit Configuration.

The crew used the remote manipulator system arm to deploy the SPARTAN-201 on the second day of the mission. SPARTAN was a free-flying science instrument platform that studied the velocity and acceleration of solar wind and observed the Sun's corona. The collected data was stored on tape for playback after return to Earth. SPARTAN was retrieved on April 13 .

Using the SAREX, the crew also contacted schools around the world and briefly contacted the Russian *Mir* space station, the first contact between the Shuttle and *Mir* using amateur radio equipment. See Table 3–77 for further mission details.

STS-55

This mission launched April 26, 1993, from Kennedy Space Center and landed May 6 at Edwards Air Force Base. This was the last launch scheduled from Pad 39-A at Kennedy Space Center until February 1994 to allow for pad refurbishment and modification. Figure 3-30 shows the STS-55 launch. On May 4, the ninth day of the mission, ground control lost all communication with *Columbia* for about 90 minutes because Mission Control issued an incorrect command.[84]

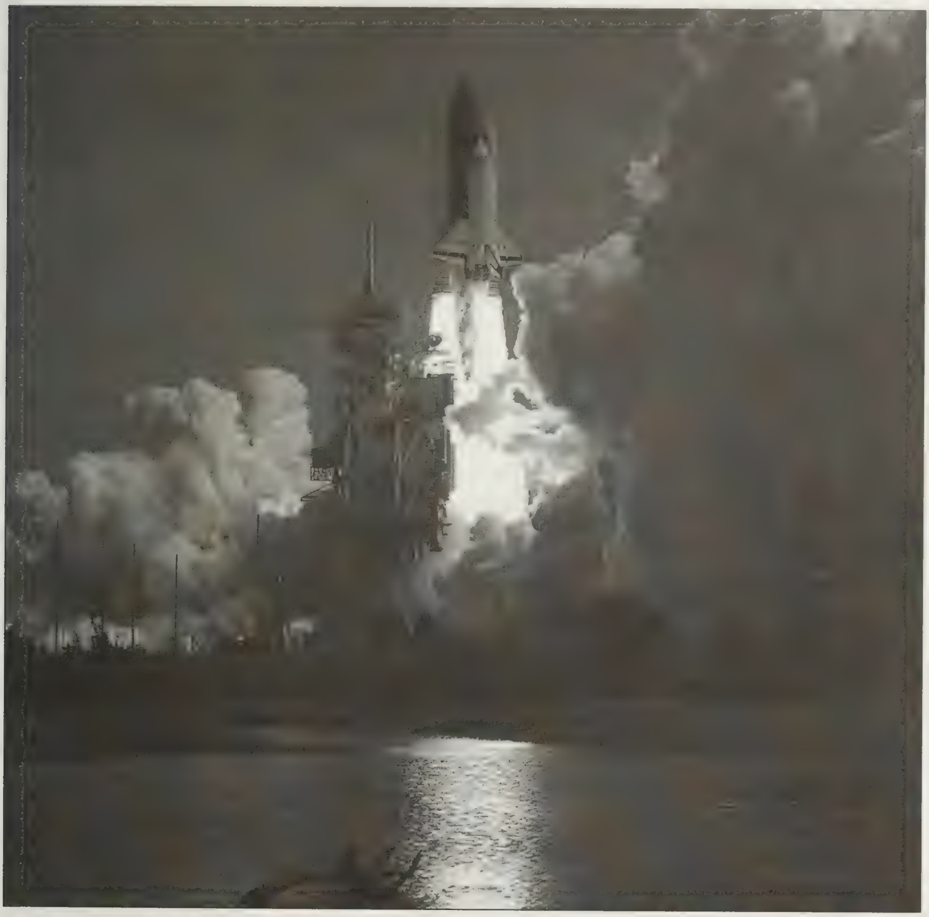

Figure 3–30. Space Shuttle Columbia *(STS-55) blasts off from Pad 39-A at Kennedy Space Center. This was the last launch from this pad until the next year to allow for pad refurbishment and modification. (NASA-KSC Photo No. KSC-93PC-0626)*

STS-55 was the second German Spacelab mission using the long module, designated D-2. Two crews worked in around-the-clock shifts and conducted approximately 88 experiments relating to materials and life sciences, technology applications, Earth observations, astronomy, and atmospheric physics. The orbiter *Columbia*, the oldest fleet member, passed its 100th day in space on this mission. See Table 3–79 for further mission details.

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[84] Jenkins, p. 304.

STS-57

This mission launched June 21 and landed July 1, 1993, at Kennedy Space Center. It was the first flight of the commercially developed SPACEHAB, a laboratory designed to more than double the pressurized workspace for crew-tended experiments.

SPACEHAB's Space Research Laboratory was situated in the forward quarter of the cargo bay. The pressurized laboratory measured approximately 10 feet (3 meters) long and 13.5 feet (4.1 meters) in diameter and contained more than 1,100 cubic feet (31.1 cubic meters) of working volume, enough to house as many as 61 middeck lockers for experiments or a combination of middeck lockers and Space Station racks. Crew members used the modified Spacelab tunnel adapter between the crew compartment and the SPACEHAB laboratory to gain access to the lab once on orbit.

The Space Research Laboratory contained all of the subsystems required to support experiment operations, including environmental controls, command and data handling, electrical power, and thermal control. On this flight, the SPACEHAB laboratory carried payloads from NASA, the U.S. commercial sector, and ESA. The crew operated a total of 22 individual experiments during the mission. Included on the flight were 13 commercial space experiments in materials processing and the effect of spaceflight on human biotechnology: 12 sponsored by the NASA CCDS and one by NASA Langley Research Center. Also on board the SPACEHAB module was an investigation sponsored by the NASA Space Station Freedom Office on closed systems to improve water recycling in the future Space Station environment.

Rendezvous and retrieval of the more than 9,000-pound (4,082-kilogram) EURECA-1 scientific satellite took place on flight day four. (See Figure 3–31 for the EURECA mission scenario.) On flight day five, astronauts David Low and Peter Wisoff spent part of a 5-hour, 55-minute EVA manually stowing the antennae, which would not respond to ground commands. The satellite had been deployed on the STS-46 mission in 1992. The crew spent the remainder of the EVA using the robot arm to complete activities associated with mass handling, mass fine alignment, and high torque. During the mission, the crew also spoke with President William J. Clinton. See Table 3–80 for further mission details.

STS-51

This mission launched on September 12 and landed on September 22, 1993, at Kennedy Space Center. The ACTS was deployed on this mission. The attached Transfer Orbit Stage booster was used for the first time to propel this communications technology spacecraft to geosynchronous transfer orbit.

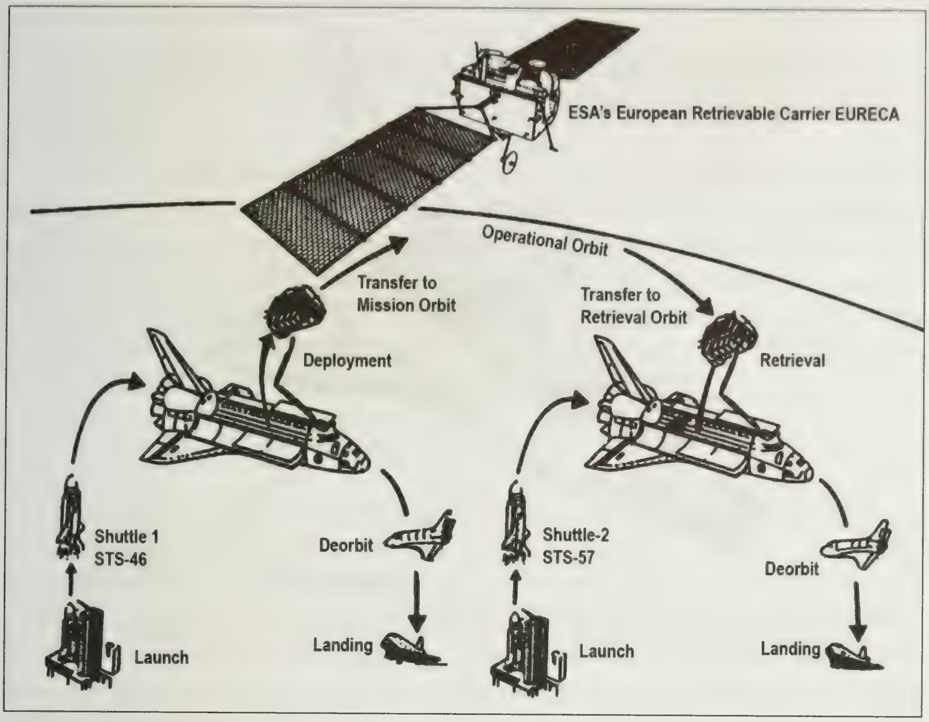
ESA's European Retrievable Carrier EURECA
Operational Orbit
Transfer to Mission Orbit
Transfer to Retrieval Orbit
Deployment
Retrieval
Shuttle 1 STS-46
Deorbit
Shuttle-2 STS-57
Deorbit
Launch
Landing
Launch
Landing

Figure 3–31. EURECA Mission Scenario. EURECA was deployed on STS-46, transferred to operational orbit, and was retrieved on the STS-57 Mission and brought back to Earth.

The second primary payload, the ORFEUS-SPAS, first in a series of ASTRO-SPAS astronomical missions, was also deployed. The joint German–U.S. astrophysics payload was controlled from the SPAS Payload Operations Control Center at Kennedy Space Center, the first time a Shuttle payload was managed from Florida. An IMAX camera mounted on SPAS recorded extensive footage of the orbiter for the first time. The crew also used the IMAX handheld camera to take out-the-window shots of the SPAS operations. After six days spent collecting data, the remote manipulator system arm retrieved the satellite and returned it to the orbiter payload bay. Figure 3–32 shows the position of the ORFEUS-SPAS and ACTS/TOS payloads in the orbiter. Figure 3–33 shows the ORFEUS-SPAS configuration.

Mission specialists James Newman and Carl Walz also performed a spacewalk that lasted 7 hours, 5 minutes, 28 seconds. Last in a series of generic spacewalks begun earlier in the year, the spacewalk's objective was to evaluate tools, tethers, and foot restraint platforms for the upcoming Hubble Space Telescope servicing mission. The findings reassured the designers and planners of the mission that their preparations were sound. See Table 3–81 for further mission details.

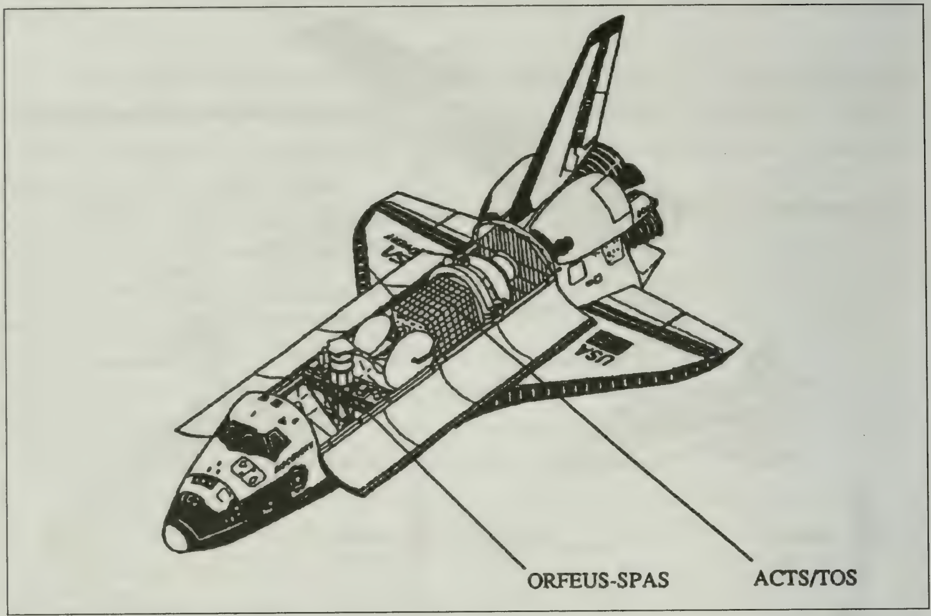
ORFEUS-SPAS
ACTS/TOS

Figure 3–32. ORFEUS-SPAS and ACTS/TOS in the Bay of Discovery *on STS-51.*

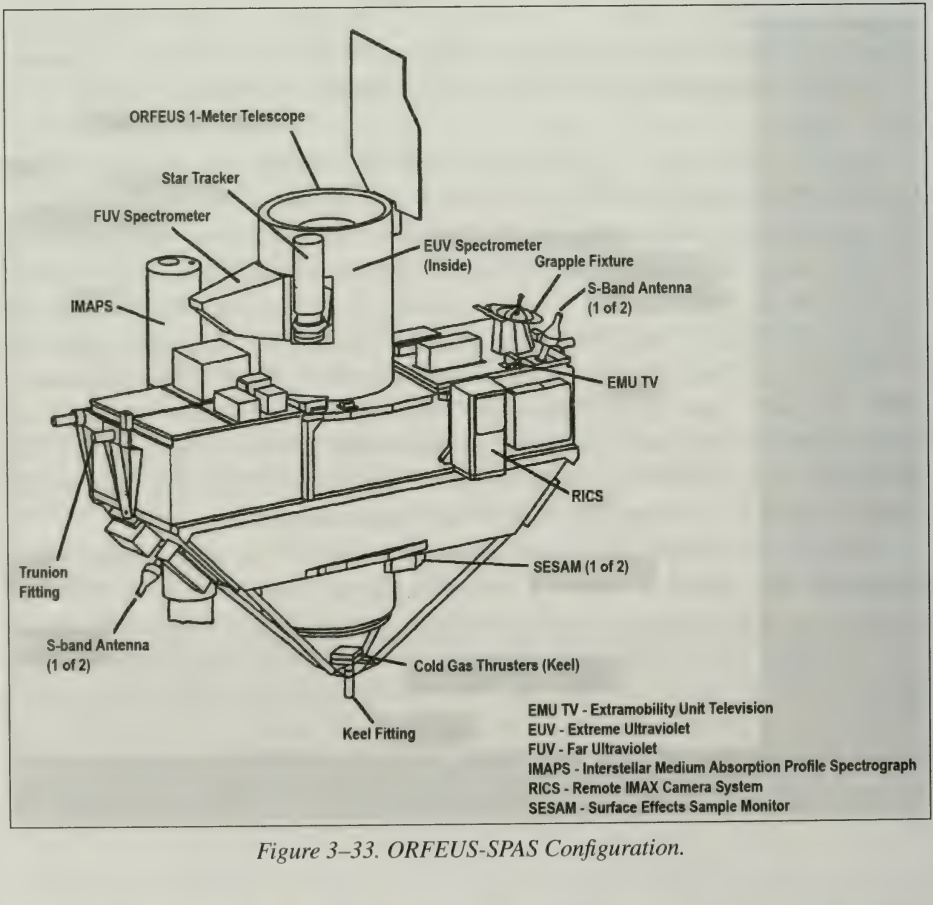
ORFEUS 1-Meter Telescope
Star Tracker
FUV Spectrometer
IMAPS
EUV Spectrometer (Inside)
Grapple Fixture
S-Band Antenna (1 of 2)
EMU TV
RICS
SESAM (1 of 2)
Trunion Fitting
S-band Antenna (1 of 2)
Cold Gas Thrusters (Keel)
Keel Fitting
EMU TV - Extramobility Unit Television
EUV - Extreme Ultraviolet
FUV - Far Ultraviolet
IMAPS - Interstellar Medium Absorption Profile Spectrograph
RICS - Remote IMAX Camera System
SESAM - Surface Effects Sample Monitor

Figure 3–33. ORFEUS-SPAS Configuration.

STS-58

This mission launched October 18, 1993, from Kennedy Space Center and landed November 1 at Edwards Air Force Base. This was the longest Shuttle flight to date.

STS-58 was the second dedicated Spacelab Life Sciences mission and the second use of the extended duration orbiter. The crew conducted 14-neurovestibular, cardiovascular, cardiopulmonary, metabolic, and musculoskeletal medical experiments. Eight of the experiments centered on the crew, and another six focused on 48 rodents carried on board. With the completion of her fourth spaceflight, astronaut Shannon Lucid accumulated the most flight time for a female astronaut on the Shuttle, 838 hours. See Table 2–82 for further mission details.

STS-61

This mission launched December 2 and landed December 13, 1993, at Kennedy Space Center. This was the first Hubble Space Telescope servicing mission, one of the most challenging and complex human spaceflight missions ever attempted. During a record five back-to-back spacewalks totaling 35 hours, 28 minutes, two teams of astronauts completed the first servicing of the Hubble Space Telescope, updating instruments, correcting the spherical aberration clouding the telescope's vision, and replacing faulty gyroscopes. Both the handheld and cargo bay IMAX cameras captured coverage of the EVAs. Footage from the cameras was used in the 2001 movie *Destiny in Space*. See Table 3–83 for further mission details.

STS-60

This mission launched February 3 and landed February 11, 1994, at Kennedy Space Center. The first Shuttle flight of 1994 marked the first flight of a Russian cosmonaut, Sergei Krikalev, on the U.S. Space Shuttle—part of the Implementing Agreement on NASA/Russian Space Agency Cooperation in HSF, an international agreement between the two countries on human spaceflight. The mission also was the second flight of the SPACEHAB pressurized module and carried the 100th GAS payload to fly in space. STS-60 flew four GAS experiments as well as three other payloads on the GAS Bridge.

Discovery also carried the WSF, an attempt to grow innovative semiconductor film materials for use in advanced electronics while in the near vacuum of space. The 12-foot (3.7-meter)-diameter parabolic-shaped WSF included a communications and avionics system, solar cells and batteries, and a propulsion thruster. It was to be deployed by the remote manipulator arm and fly in formation with *Discovery* at a distance of up to 46 statute miles (74 kilometers) from the orbiter for 56 hours. The remote manipulator arm was supposed to retrieve the WSF from space. However, after two unsuccessful attempts to deploy the facility, it was decided that for the remainder of the mission, all WSF operations would take place at the end of the remote manipulator system and there would be no WSF free-flying operations. See Table 3–84 for further mission details.

STS-62

This mission launched March 4 and landed March 18, 1994, at Kennedy Space Center. The primary payloads were the USMP-2 and the OAST-2 suite of experiments. USMP-2 included five experiments investigating materials processing and crystal growth in microgravity. OAST's six experiments focused on space technology and spaceflight. Both payloads were located in the payload bay, activated by crew members, and operated by teams on the ground.

The USMP-2 experiments were conducted early in the mission. Later, to facilitate the OAST-2 experiments, *Columbia*'s orbit was lowered about 20 nautical miles (37 kilometers). The crew also conducted a number of biomedical activities aimed at better understanding and countering the effects of prolonged spaceflight. See Table 3–85 for further mission details.

STS-59

This mission launched April 9, 1994, from Kennedy Space Center and landed April 20 at Edwards Air Force Base. The SRL-1 was this mission's primary payload. It gathered data on Earth and the effect of humans on the planet's carbon, water, and energy cycles. SRL-1 was located in the Shuttle's payload bay, activated by crew members, and operated by teams on the ground. SRL-1 included an atmospheric instrument called the Measurement of Air Pollution from Satellites (MAPS), the Spaceborne Imaging Radar-C (SIR-C), and the X-band Synthetic Aperture Radar (X-SAR). Figure 3–34 shows the location of the X-SAR panels and the SIR-C-band and L-band panels on the payload bay pallet. The German Space Agency and the Italian Space Agency provided the X-SAR. More than 400 sites were imaged, including 19 primary observation sites (supersites) in Brazil, Michigan, North Carolina, and Central Europe. The total area covered was 25.6 million square miles (~50 million square kilometers).[85] Thirteen countries were represented in the project with 49 principal investigators and more than 100 scientists, coordinated by the Jet Propulsion Laboratory (JPL). Roughly 65 hours of data were collected.[86] The MAPS experiment measured the global distribution of carbon monoxide in the troposphere, or lower atmosphere.

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[85] "SIR-C/X-SAR Flight 1 Statistics," JPL Fact Sheet, *http://southport.jpl.nasa.gov/sir-c/getting_data/missions_stats.html* (accessed December 7, 2005). Also e-mails from Bruce Chapman, JPL, December 7, 2005.

[86] "SIR-C/X-SAR Flight 1 Statistics," JPL Fact Sheet.

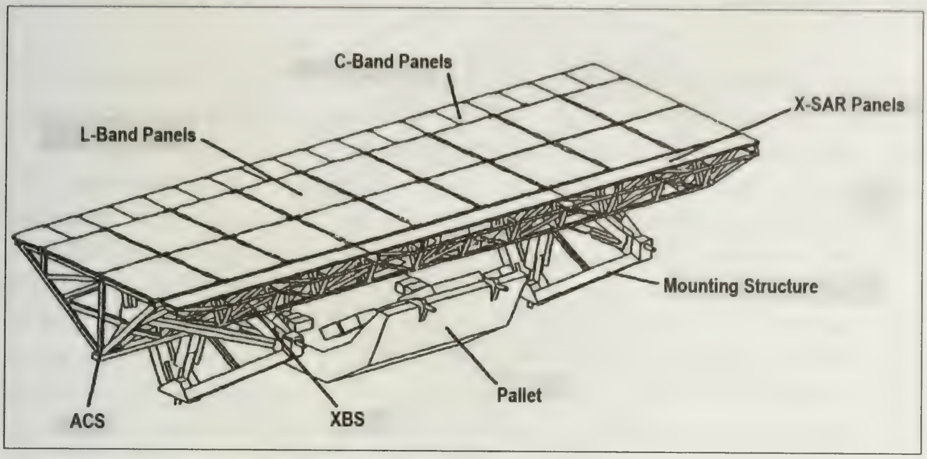
C-Band Panels
X-SAR Panels
L-Band Panels
Mounting Structure
Pallet
ACS
XBS

Figure 3–34. The SIR and X-SAR located on a Spacelab pallet in the Shuttle's payload bay on STS-59.

This was the first flight test of an improved thermal protection tile. Known as Toughened Uni-Piece Fibrous Insulation (TUFI), the new tile material was an advanced version of the material protecting the Space Shuttle from the intense heat that built up as it reentered Earth's atmosphere. On this mission, six tiles located on the triangular carrier panel between and below two of the main engines sustained no damage.[87] Figure 3–35 shows the location of the various payloads on *Endeavour*. See Table 3–86 for further mission details.

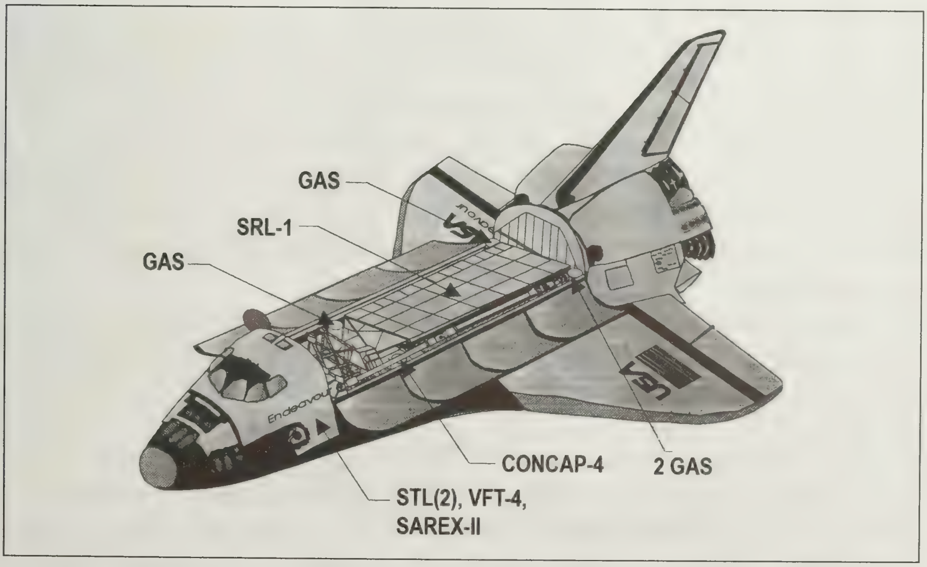
GAS
SRL-1
GAS
CONCAP-4
2 GAS
STL(2), VFT-4,
SAREX-II

Figure 3–35. Payloads on Endeavour *(STS-59).*

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[87] "STS-59 Shuttle Mission Report," June 1994, NSTS-08291, NASA-TM-110527, p. 25, *http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19950016676_1995116676.pdf* (accessed July 7, 2005).

STS-65

This mission launched July 8 and landed July 23, 1994, at Kennedy Space Center. This was *Columbia*'s last mission before its scheduled modification and refurbishment. The first female Japanese astronaut, Chiaki Naito-Mukai, flew on this mission. She set a record for the longest flight by a female astronaut. This flight also marked the first time that liftoff and reentry were captured on videotape from the crew cabin. The flight was the longest to date, lasting 14 days, 18 hours.

The IML-2 was the primary payload. The IML-2 carried more than twice the number of experiments and facilities as the first IML mission. More than 80 experiments, representing more than 200 scientists from six space agencies, were located in the IML Spacelab module in the payload bay. Two teams of crew members performed round-the-clock research on the behavior of materials and life in near weightlessness.

Fifty of the experiments related to life sciences, including bioprocessing, space biology, human physiology, and radiation biology. Some of the equipment used for these investigations had flown on previous Spacelab flights, such as ESA's Biorack, making its third flight. The IML-2 Biorack housed 19 experiments featuring chemicals and biological samples such as bacteria; mammalian and human cells; isolated tissues and eggs; sea urchin larvae; fruit flies; and plant seedlings.

DARA provided the Slow Rotating Centrifuge Microscope (NIZEMI), a slow-rotating centrifuge that allowed study of how organisms react to different gravity levels. Samples studied included jellyfish and plants. For the first time, researchers could determine how organisms reacted to forces one and one-half times Earth's gravity.

Nearly 30 experiments in materials processing were conducted with nine different types of science facilities. DARA provided the Electromagnetic Containerless Processing Facility (TEMPUS), flying for the first time on IML-2, to allow study of the solidification of materials from the liquid state in a containerless environment. Solidification phenomena were of great interest to science and also used in many industrial processes. Science teams detected for the first time a phase in a nickel-niobium sample that was masked by other forces on Earth.

Another facility, the ESA's APCF, was flying for the second time. Housed in two middeck lockers, the APCF operated autonomously after being activated on the first flight day. Some 5,000 video images were made of crystals grown during flight.

The mission further advanced the concept of telescience, where researchers on the ground could monitor in real time experiments on board the orbiter. The flight set a new record of more than 25,000 payload commands issued from Spacelab Mission Operations Control at Huntsville, Alabama. Figure 3–36 shows the layout of the IML-2 module racks. See Table 3–87 for further mission details.

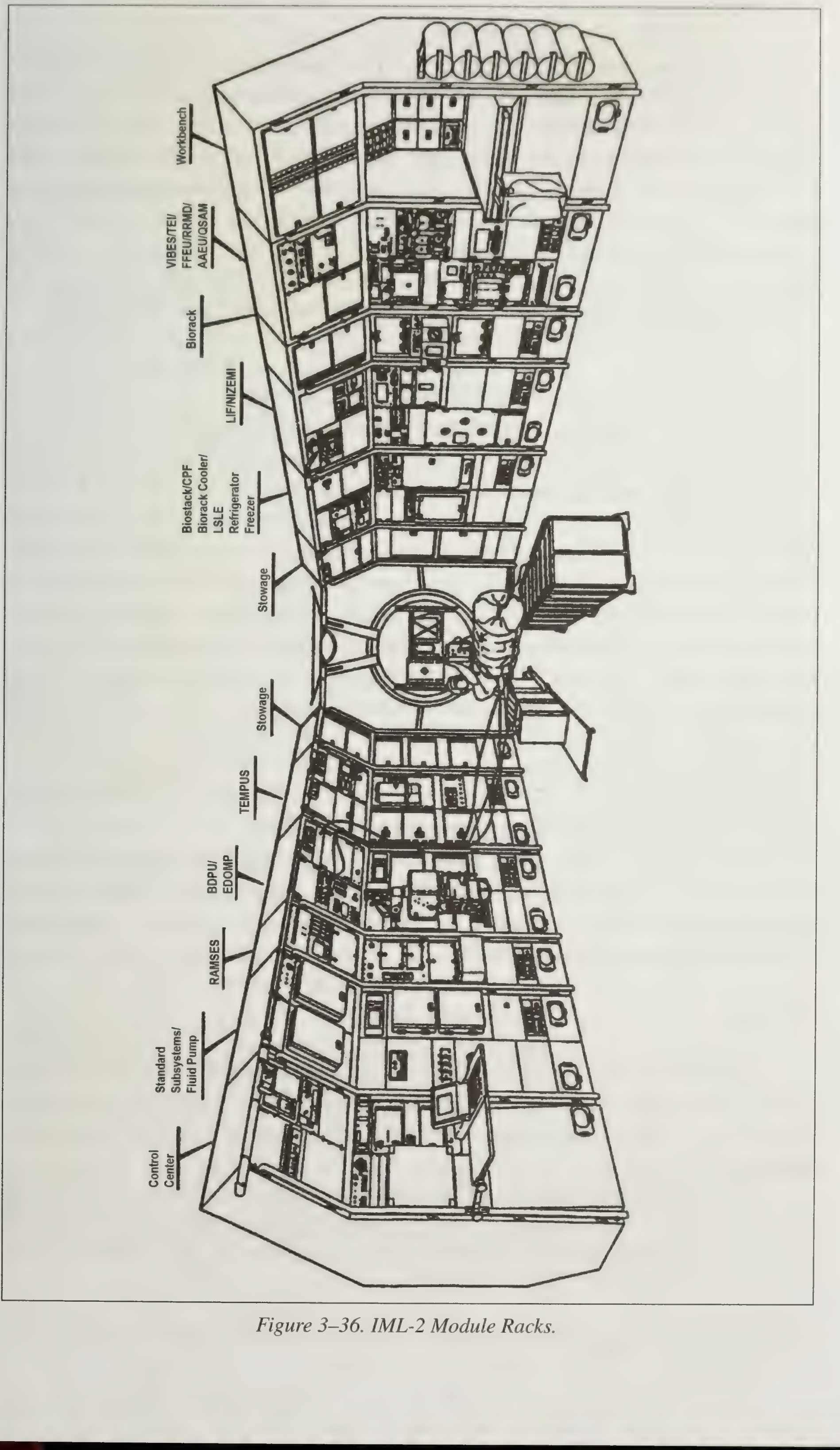
Control Center
Standard Subsystems/ Fluid Pump
RAMSES
BDPU/ EDOMP
TEMPUS
Stowage
Stowage
Biostack/CPF Biorack Cooler/ LSLE Refrigerator Freezer
LIF/NIZEMI
Biorack
VIBES/TEI/ FFEU/RRMD/ AAEU/QSAM
Workbench

Figure 3–36. IML-2 Module Racks.

STS-64

This mission launched September 9, 1994, from Kennedy Space Center and landed September 20 at Edwards Air Force Base. STS-64 marked the first flight of the LIDAR LITE, which used laser optical radar for the first time to perform atmospheric research as part of NASA's Mission to Planet Earth program. The LITE operated for 53 hours and yielded more than 43 hours of high-rate data. Sixty-five groups from 20 countries made validation measurements with ground-based and aircraft instruments to verify LITE data. During the mission, the crew also released and retrieved the SPARTAN-201 satellite using the remote manipulator system arm. See Table 3–88 for further mission details.

STS-68

This mission launched September 30, 1994, from Kennedy Space Center and landed October 11 at Edwards Air Force Base. The mission set another duration record, lasting more than 16.5 days. The SRL-2, part of NASA's Mission to Planet Earth, flew for the second time in the same year. It gathered data on Earth and the effect of humans on the planet's carbon, water, and energy cycles. Flying the laboratory in different seasons allowed investigators to compare observations between the two flights, which took place in mid-April and at the end of September. The mission also tested the ability of SRL-2's imaging radar to distinguish between changes caused by human-induced phenomena, such as oil spills, and naturally occurring events. The mission demonstrated the maneuvering capability of the orbiter as the crew piloted the *Endeavour* to within 30 feet (9.1 meters) of where it had flown during the first SRL mission on STS-59. The total area covered on this mission was 32 million square miles (roughly 83 million square kilometers).[88]

Five GAS payloads were among the other cargo bay payloads. They included two canisters from the U.S. Postal Service that held 500,000 commemorative stamps honoring the 25th anniversary of Apollo 11. See Table 3–89 for further mission details.

STS-66

This mission launched November 3, 1994, from Kennedy Space Center and landed November 14 at Edwards Air Force Base. The landing was diverted to Edwards Air Force Base because of Tropical Storm Gordon, which prevented landing in Florida.

ATLAS-3, the third ATLAS flight, sat on a Spacelab pallet in the Shuttle cargo bay and collected data about the Sun's energy output, the chemical makeup of Earth's middle atmosphere, and how these factors affected global ozone levels. The second primary payload, the CRISTA-SPAS, was released on the second day of the mission and retrieved with the Shuttle's remote manipulator system arm. This payload continued the joint NASA-German Space Agency series of scientific missions. CRISTA-SPAS flew at a distance of about 25 miles to 44 miles (40 kilometers to 70 kilometers) behind the Shuttle and collected data for more than eight days before being retrieved and returned to the cargo bay. See Table 3–90 for further mission details.

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[88] "SIR-C/X Flight 2 Statistics," *http://southport.jpl.nasa.gov/sir-c/getting_data/missions_stats.html* (accessed December 7, 2005).

STS-63

This mission launched February 3 and landed February 11, 1995, at Kennedy Space Center. On this flight, Eileen Collins became the first female to serve as a Shuttle pilot.

STS-63 had special importance as a precursor and dress rehearsal for the Shuttle missions that would rendezvous and dock with the Russian space station *Mir.* After flying to and "stationkeeping" at 400 feet (122 meters) from *Mir, Discovery* approached to 37 feet (11 meters) before backing off to 400 feet (122 meters) and performing a fly-around. The six-person Shuttle crew included Vladimir Titov, the second Russian cosmonaut to fly on the Space Shuttle. (Figure 3-37 shows the *Mir* space station as seen from *Discovery.*) Crew members Bernard Harris, Jr., and C. Michael Foale performed a spacewalk away from the payload bay to test spacesuit modifications intended to keep spacewalkers warmer and to demonstrate large-object handling techniques. The mass-handling part of the EVA was curtailed when the astronauts became very cold. Harris became the first African-American to walk in space.

The mission also deployed SPARTAN-204, a free-flying spacecraft that made astronomical observations in the far ultraviolet spectrum (see Figure 3–38).

The SPACEHAB module flew for the third time with an array of technological, biological, and other scientific experiments. SPACEHAB introduced two new system features to reduce the demands on crew time. The first was a video switch allowing one camcorder to transmit images to the ground at the same time another unit collected a digital image on a freeze frame and sent it down independently of other orbiter video downlink operations. The second, an enhanced experiment data interface with the SPACEHAB telemetry system, allowed an experimenter with a standard RS232 computer interface to tie directly into the system and send continuous information down to the ground, off-loading this task from the crew and enhancing ground controller monitoring of experiment status. The SPACEHAB laboratory on this mission had two 12-inch (30.5-centimeter)-diameter windows with a NASA docking camera to assist in *Mir* proximity operations. See Table 3–91 for further mission details.

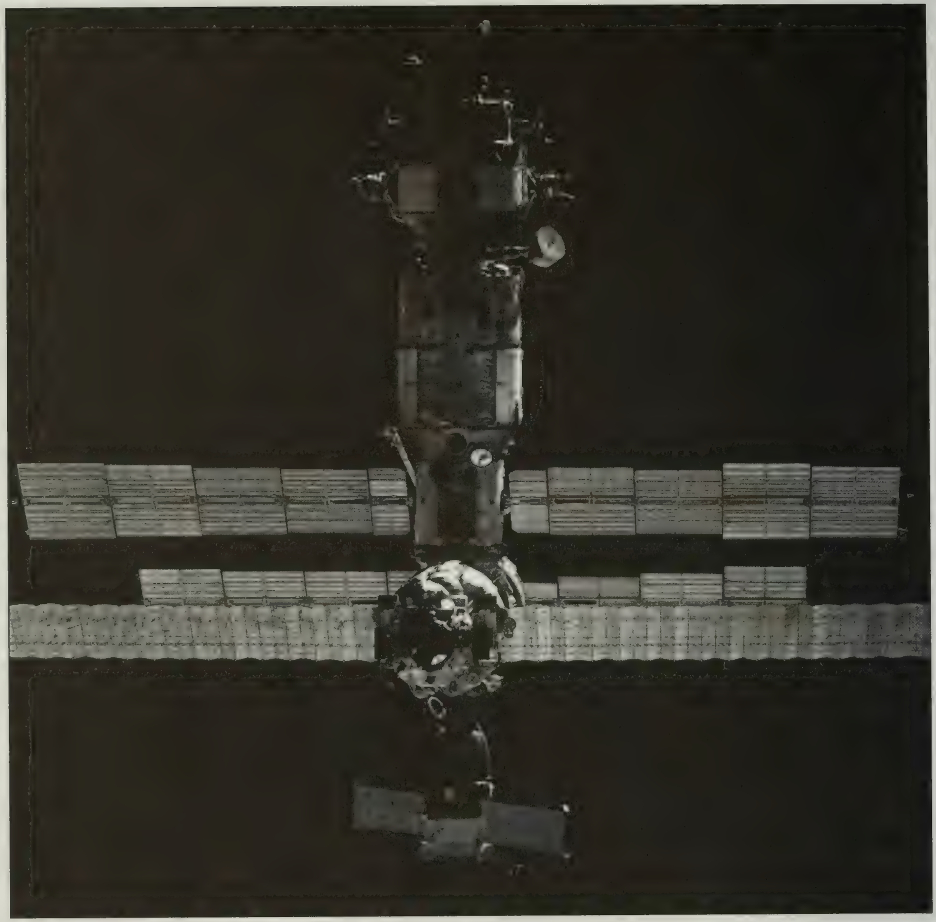

Figure 3–37. Russia's Mir *Space Station during rendezvous operations with the Space Shuttle* Discovery. *Docked at the bottom of the* Mir *facility is a Soyuz vehicle. On STS-63,* Discovery *approached* Mir, *flew around the Russian Space Station, and then backed off. This provided practice for future docking missions. (NASA Photo STS063-712-017)*

STS-67

This mission launched March 2, 1995, from Kennedy Space Center and landed March 18 at Edwards Air Force Base. The mission set a duration record of more than 16.5 days.

Astro-2 was the second mission using the Spacelab instrument pointing system and igloo/pallet to conduct astronomical observations and obtain scientific data on astronomical objects in the ultraviolet regions of the spectrum. The Spacelab's three telescopes made observations in complementary regions of the spectrum and gathered data that would add to scientists' understanding of the universe's history and the origins of stars. Figure 3–39 shows the Astro-2 suite of instruments.

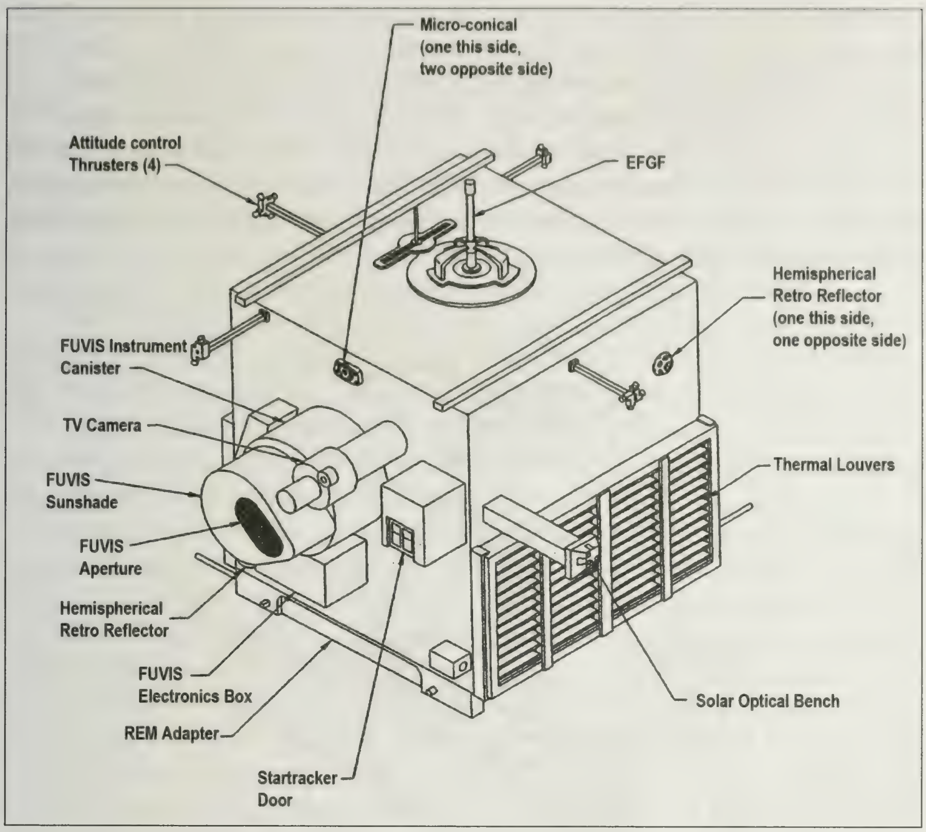
Micro-conical (one this side, two opposite side)
Attitude control Thrusters (4)
EFGF
Hemispherical Retro Reflector (one this side, one opposite side)
FUVIS Instrument Canister
TV Camera
Thermal Louvers
FUVIS Sunshade
FUVIS Aperture
Hemispherical Retro Reflector
FUVIS Electronics Box
REM Adapter
Solar Optical Bench
Startracker Door

Figure 3–38. SPARTAN-204 was a free-flying spacecraft that observed the far ultraviolet spectrum. Weighing some 2,500 pounds (1,134 kilograms), it was to give the astronauts practice handling heavy loads in the cold, nighttime space environment in preparation for Space Station assembly. But both astronauts reported they were becoming very cold, and the mass handling part of the mission was curtailed

STS-67 was the first advertised Shuttle mission connected to the Internet. Users of more than 200,000 computers from 59 countries logged on to the Astro-2 home page at Marshall Space Flight Center. More than 2.4 million requests were recorded during the mission, many answered by the crew in-orbit. See Table 3–92 for further mission details.

STS-71

This mission launched June 27 and landed July 7, 1995, at Kennedy Space Center. This flight marked the 100th U.S. human spaceflight and was the first in a series of Shuttle flights that docked with the Russian space station *Mir*. After docking on flight day three, *Mir* and *Atlantis* remained joined for five days. The seven-person Shuttle crew included two Russian cosmonauts who remained on *Mir* after *Atlantis* returned to Earth. Two other cosmonauts and the U.S.

astronaut Norman Thagard, who had flown to *Mir* aboard the Russian Soyuz spacecraft in March 1995, returned to Earth on *Atlantis* after more than 100 days in space. To ease their return to gravity, the three lay on their backs on specially designed seats installed in the orbiter's middeck. The returning crew of eight equaled the largest crew to fly on the Shuttle. The mission demonstrated the successful operation of the Russian-designed docking system, which was based on concepts used during the Apollo-Soyuz Test Project in 1975. See Table 3–93 for further mission details.

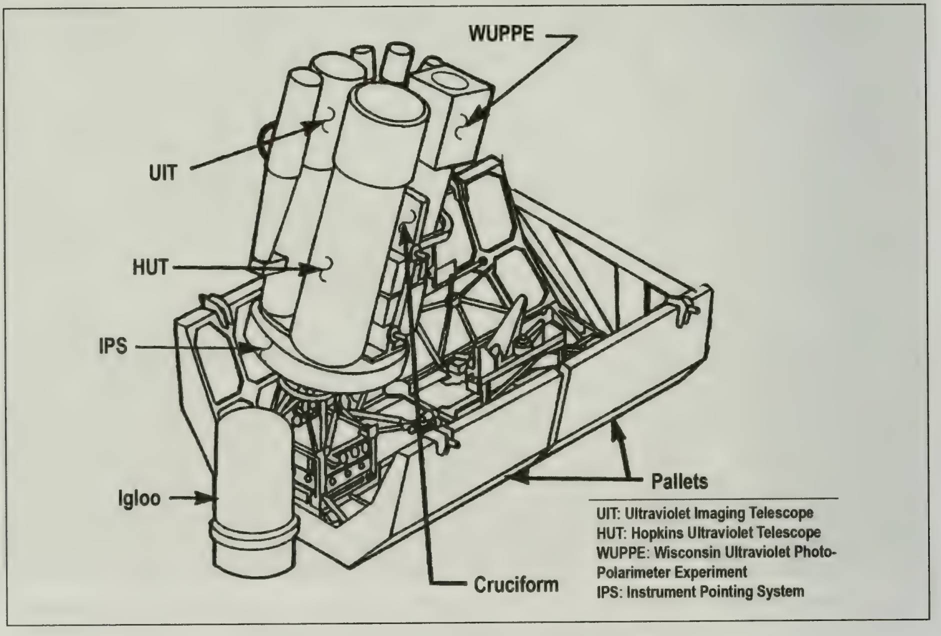
WUPPE
UIT
HUT
IPS
Igloo
Pallets
Cruciform
UIT: Ultraviolet Imaging Telescope
HUT: Hopkins Ultraviolet Telescope
WUPPE: Wisconsin Ultraviolet Photo-Polarimeter Experiment
IPS: Instrument Pointing System

Figure 3–39. Astro-2 Suite of Instruments.

STS-70

This mission launched July 13 and landed July 22, 1995, from Kennedy Space Center. The TDRS-7 deployment marked completion of NASA's TDRS system, which provided communication, tracking, telemetry, data acquisition, and command services to the Shuttle and other low orbital spacecraft missions from geosynchronous orbit. STS-70 also marked the first flight of the new Block I Space Shuttle Main Engine. The engine featured a new high-pressure, liquid oxygen turbopump, two-duct powerhead, baffleless main injector, single-coil heat exchanger, and start sequence modifications that increased its stability and safety. See Table 3–94 for further mission details.

STS-69

This mission launched September 7 and landed September 18, 1995, at Kennedy Space Center. The Shuttle deployed the WSF-2, which, flying separately from the Shuttle, produced an "ultravacuum" in its wake and allowed experimentation in the production of advanced, thin film semiconductor materials. The WSF-2, deployed on flight day five, became the first spacecraft to maneuver itself away from the orbiter (rather than the other way around) by firing a small cold gas nitrogen thruster to move away from *Endeavour*.

The SPARTAN 201-03 also was deployed and retrieved. The SPARTAN's primary objective was to study the outer atmosphere of the Sun and its transition into the solar wind that constantly flows past Earth. The timing of the SPARTAN flight was intended to coincide with the passage of the Ulysses spacecraft over the Sun's north polar region to expand the range of data being collected about the origins of the solar wind.

During the spacewalk on this mission, which lasted 6 hours, 46 minutes, astronauts James Voss and Michael Gernhardt evaluated the thermal improvements made to their EVA suits and reported that they remained comfortable. They also tested a variety of tools and techniques perhaps necessary for ISS assembly. The spacewalk was the 30th EVA of the Shuttle program.

STS-69 also was the second flight of a "dog crew," a flight crew tradition that began on STS-53, on which both Walker and Voss flew. As Dog Crew II, each STS-69 astronaut adopted a dogtag or nickname: Walker was Red Dog; Cockrell was Cujo; Voss, Dog Face; Newman, Pluto; and Gernhardt, Under Dog. See Table 3–95 for further mission details.

STS-73

This mission launched October 20 and landed November 5, 1995, at Kennedy Space Center. USML-2, the second United States Microgravity Laboratory, was the primary payload. Some of the experiments resulted from the outcome of investigations on USML-1, which flew aboard *Columbia* on STS-50. The research during USML-2 concentrated on the same overall areas as USML-1, and many experiments flew for the second time. Research was conducted in five areas: fluid physics, materials science, biotechnology, combustion science, and commercial space processing. Two teams of crew members worked around-the-clock in the 23-foot (7-meter) Spacelab module located in *Columbia*'s payload bay.

The crew took time out from Spacelab work to tape the ceremonial first pitch for Game 5 of the Major League Baseball World Series, marking the first time the thrower was not actually in the ballpark for the pitch. This was the second longest Shuttle flight to date. See Table 3–96 for further mission details.

STS-74

This mission launched November 12 and landed November 20, 1995, at Kennedy Space Center. It was the second in a series of dockings with *Mir.* The mission marked the first time that astronauts from ESA, Canada, Russia, and the United States were in space on the same complex at one time.

Unlike the first docking flight during which a crew exchange took place, the second docking focused on delivery of equipment to *Mir.* The primary payload of the mission was the Russian-built Docking Module (DM), designed to become a permanent extension on *Mir* to afford better clearances for Shuttle-*Mir* linkups. Two solar arrays were stowed on the DM for later transfer to *Mir* by spacewalking cosmonauts. See Table 3–97 for further mission details.

STS-72

This mission launched January 11 and landed January 20, 1996, at Kennedy Space Center. The crew of STS-72 captured and returned to Earth a Japanese microgravity research spacecraft, the Space Flyer Unit, which had been launched by Japan in March 1995. The mission also deployed and retrieved the OAST-Flyer spacecraft, the seventh in a series of missions aboard reusable, free-flying SPARTAN carriers. The flight also included two spacewalks to test hardware and tools to be used during ISS assembly. See Table 3–98 for further mission details.

STS-75

The mission launched February 22 and landed March 9, 1996, at Kennedy Space Center. The mission was the 50th Shuttle flight since NASA's return to flight following the *Challenger* accident and the 75th Shuttle flight. The mission was a reflight of the TSS (see STS-46). The tether broke three days into the mission, just short of its full deployment length, resulting in the loss of the Italian satellite.

The other primary Shuttle payload was USMP-3, the third United States Microgravity Payload. The payload included U.S. and international experiments, all of which had flown at least once before. See Table 3–99 for further mission details.

STS-76

This mission launched March 22, 1996, from Kennedy Space Center and landed March 31 at Edwards Air Force Base. The mission, Shuttle-*Mir* Mission 3, featured the third docking of the Space Shuttle *Atlantis* and the Russian space station *Mir.* Docking occurred between the ODS in the forward area of the *Atlantis* payload bay and the DM installed during STS-74 on *Mir*'s Kristall module docking port. The mission included a spacewalk, logistics operations, and scientific research. About 1,500 pounds (680 kilograms) of water and two tons of scientific equipment, logistical material, and resupply items were transferred from *Atlantis* to *Mir*, including a gyrodyne, transformer, batteries, food, water, film, and clothing. Experiment samples and miscellaneous equipment were brought to *Atlantis* from *Mir*. Astronaut Shannon Lucid, the second U.S. astronaut and the first U.S. woman to live on the Russian space station, began what turned out to be a marathon stay on *Mir* of four and one-half months, eclipsing the previous record set by Norman Thagard.

STS-76 marked the first flight of a SPACEHAB pressurized module to support Shuttle-*Mir* dockings. The single module served primarily as stowage area for a large supply of equipment slated for transfer to the Space Station. It also carried ESA's Biorack experiment rack for on-orbit research.

This mission experienced an unusual anomaly on the orbiter's ride back from Edwards Air Force Base to Kennedy Space Center after the Shuttle flight. A warning light for an engine on the Shuttle Carrier Aircraft 747 indicated an engine fire. The plane returned to Edwards Air Force Base, and the engine was replaced before the journey recommenced. See Table 3–100 for further mission details.

STS-77

This mission launched May 19 and landed May 29, 1996, at Kennedy Space Center. This was the first flight that used three Block I main engines and the first Shuttle mission controlled from the new Mission Control Center at Johnson Space Center. The new facility replaced the Apollo-era complex that had been used for previous Shuttle missions.

The mission was highlighted by four rendezvous activities with two different payloads: deployment and retrieval of the Passive Aerodynamically Stabilized Magnetically Damped Satellite (PAMS), one of four Technology Experiments for Advancing Missions in Space (TEAMS), and of the SPARTAN 207/Inflatable Antenna Experiment (IAE) satellite. During its 90-minute mission, the IAE tested the performance of a large inflatable antenna, laying the groundwork for future technology development on inflatable space structures. At the end of the mission, the crew jettisoned the antenna structure and stowed the spacecraft.

The six-person *Endeavour* crew also performed microgravity research aboard the SPACEHAB module. The single module carried almost 3,000 pounds (1,361 kilograms) of experiments and support equipment for 12 commercial space product development payloads in the areas of biotechnology, electronic materials, polymers, and agriculture. One of the additional payloads, the Commercial Float Zone Facility, was an international collaboration between the United States, Canada, and Germany. See Table 3–101 for further mission details.

STS-78

This mission launched June 20 and landed July 7, 1996, at Kennedy Space Center. Five space agencies (NASA, ESA, the French Space Agency—CNES, the CSA, and the Italian Space Agency) and research scientists from 10 countries worked together on the LMS Spacelab, which built on previous Shuttle Spacelab flights dedicated to life sciences and microgravity investigations. More than 40 experiments were flown and grouped into the areas of life sciences, which included the following: human physiology and space biology; microgravity science (including basic fluid physics investigations and advanced semiconductor and metal alloy materials processing); and medical research in protein crystal growth. The investigations focused on the effects of long-duration spaceflight on human physiology, and crew members conducted the types of experiments that would fly on the ISS. LMS investigations were conducted via the most extensive telescience to date. Investigators were located at four remote European and four remote U.S. locations, similar to what would happen with the ISS. The mission also made extensive use of video imaging to help crew members perform in-flight maintenance procedures on experiment hardware. This was the longest Shuttle flight flown, lasting almost 17 days. See Table 3–102 for further mission details.

STS-79

This mission launched September 16 and landed September 26, 1996, at Kennedy Space Center. On this mission, astronaut Shannon Lucid set the world's women's and U.S. records for length of time in space: 188 days and 5 hours. The mission was the fourth Shuttle docking with the *Mir* space station and the first exchange of U.S. crew aboard a Russian spacecraft. Lucid returned to Earth on *Atlantis*, and astronaut John Blaha replaced her on *Mir* for a planned four-month stay.

The mission also marked the second flight of the SPACEHAB module in support of Shuttle-*Mir* activities and the first flight of the SPACEHAB double module configuration. During five days of mated operations, the two crews transferred more than 4,000 pounds (1,814 kilograms) of supplies to *Mir*, including logistics, food, and water generated by orbiter fuel cells. Three experiments also were transferred: Biotechnology System (BTS) for study of cartilage development; Material in Devices as Superconductors (MIDAS) to measure electrical properties of high-temperature superconductor materials; and CGBA, which contained several smaller experiments including self-contained aquatic systems. About 2,000 pounds (907 kilograms) of experiment samples and equipment were transferred from *Mir* to *Atlantis*. The total logistical transfer to and from *Mir* of more than 6,000 pounds (2,722 kilograms) was the most extensive to date. See Table 3–103 for further mission details.

STS-80

This mission launched November 19 and landed December 7, 1996, at Kennedy Space Center. This was the third flight of the WSF, which had flown on STS-60 and STS-69. It was the second flight of the German-built ORFEUS-SPAS-2. Both the WSF and ORFEUS-SPAS were deployed and retrieved during the mission, making it the first time that two satellites were flying freely at the same time. ORFEUS-SPAS II was the third flight to use the German-built ASTRO-SPAS science satellite. The 1-meter (3.1-foot)-diameter ORFEUS-Telescope with the Far Ultraviolet (FUV) Spectrograph and the Extreme Ultraviolet (EUV) Spectrograph comprised the main payload attached to the ASTRO-SPAS framework. The Interstellar Medium Absorption Profile Spectrograph (IMAPS) was a separate instrument, IMAPS operated independently of the ORFEUS telescope. Another science payload was the Surface Effects Sample Monitor (SESAM), a passive carrier for state-of-the-art optical surfaces and potential future detector materials. The SESAM investigated the impact of the space environment on materials and surfaces in different phases of a Space Shuttle mission, from launch to orbit phase to reentry into Earth's atmosphere.

Two planned 6-hour EVAs were canceled because of a jammed outer airlock hatch. This flight again broke the record for the longest Shuttle flight, lasting slightly more than 17.5 days. See Table 3–104 for further mission details.

STS-81

This mission launched January 12 and landed January 22, 1997, at Kennedy Space Center. STS-81 was the fifth of nine planned missions to *Mir* and the second involving an exchange of U.S. astronauts. Astronaut Jerry Linenger replaced astronaut John Blaha aboard *Mir* after Blaha spent 118 days on *Mir* and 128 days in space. *Atlantis* carried the SPACEHAB double module, which provided additional middeck locker space for experiments. While the vehicles were docked, crews transferred nearly 6,000 pounds (2,722 kilograms) of logistics to *Mir*, including approximately 1,600 pounds (726 kilograms) of water, 1,138 pounds (516 kilograms) of U.S. science equipment, and 2,206 pounds (1,000 kilograms) of Russian logistical equipment. About 2,400 pounds (1,089 kilograms) of materials returned from *Mir* to Earth on *Atlantis*. See Table 3–105 for further mission details.

STS-82

This mission launched February 11 and landed February 21, 1997, at Kennedy Space Center. It was the second in a series of planned servicing missions to the Hubble Space Telescope. The orbiter's robot arm captured the Hubble Space Telescope so it could be serviced, and two teams of astronauts performed five spacewalks. The crew took more than 150 crew aids and tools on the mission, ranging from a simple bag for carrying some of the smaller tools to sophisticated battery-operated power tools. See Table 3–106 for further mission details.

STS-83

This mission launched April 4 and landed April 8, 1997, at Kennedy Space Center. This mission lasted only 4 days and returned to Earth 12 days early because of a problem with one of the fuel cells that provided electricity and water to the orbiter. The MSL-1 was rescheduled for STS-94. See Table 3–107 for further mission details.

STS-84

This mission launched May 15 and landed May 24, 1997, at Kennedy Space Center. This was the sixth docking with the *Mir* space station and the third involving an exchange of U.S. astronauts. Astronaut J. Michael Foale replaced astronaut Jerry Linenger, who had been in space 132 days. The mission resupplied materials for experiments to be performed aboard *Mir* and returned experiment samples and data to Earth. Altogether nearly 249 items were moved between the two spacecraft, with nearly 1,000 pounds (565 kilograms) of water moved to *Mir*, for a total of nearly 7,500 pounds (3,402 kilograms) of water, experiment samples, supplies, and hardware. See Table 3–108 for further mission details.

STS-94

This mission launched July 1 and landed July 17, 1997, at Kennedy Space Center. It was the reflight of MSL-1, which had flown on STS-83. The mission involved the same vehicle, crew, and experiment activities as planned on the earlier MSL-1 mission. The crew maintained 24-hour/two-shift operations. Using the Spacelab module as a testbed, the MSL-1 tested some of the hardware, facilities, and procedures that would be used on the ISS. The 33 investigations also yielded new knowledge in the fields of combustion, biotechnology, and materials processing. Scientists from NASA, ESA, the German Space Agency, and the National Space Development Agency of Japan contributed the 25 primary experiments, 4 glovebox investigations, and 4 accelerometer studies on MSL-1. A record number of commands—more than 35,000—were sent from the Spacelab Mission Operations Control Center at Marshall Space Flight Center to the MSL-1. See Table 3–109 for further mission details.

STS-85

This mission launched August 7 and landed August 19, 1997, at Kennedy Space Center. The CRISTA-SPAS-2 was the primary payload. It was deployed and, after more than 200 hours of free flight, was retrieved using *Discovery*'s robot arm. (See Figure 3–40 for a drawing of the SPAS-2.) CRISTA-SPAS-2 was the fourth in a series of cooperative ventures between the German Space Agency and NASA. This was the satellite's second flight. The satellite consisted of three telescopes and four spectrometers. The three CRISTA telescopes collected 38 full atmospheric profiles of the middle atmosphere. Two other instruments mounted on the SPAS also studied Earth's atmosphere. The MAHRSI obtained new vertical profile data on the distribution of hydroxyl (OH) and nitric oxide in the mesosphere and upper stratosphere conditions under very different (both seasonal and diurnal) from its previous flight on STS-66. The SESAM carried state-of-the-art optical surfaces to study the impact of the atomic oxygen and space environment on materials and services. Twenty-two sounding rockets and 40 balloons were launched to provide correlating data.

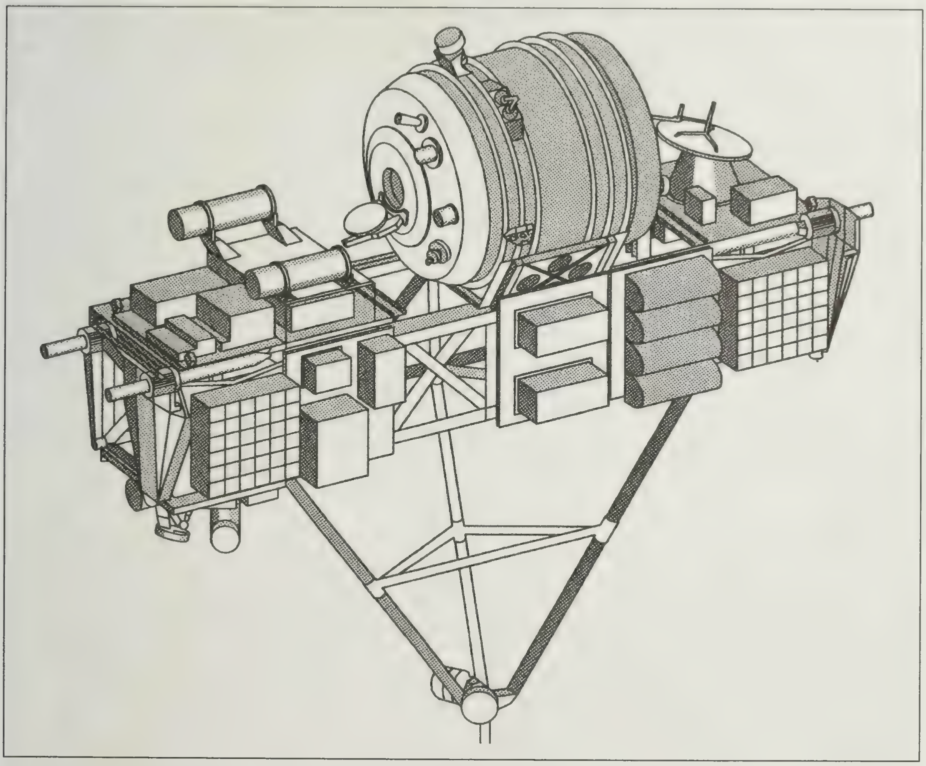

Figure 3–40. The SPAS-2 was a German-built, reusable free-flying vehicle that could be deployed and retrieved by the Space Shuttle's Remote Manipulator System. The original SPAS was used on STS-7 with materials processing and defense-related sensor payloads. The SPAS-2 was used on ORFEUS-SPAS and CRISTA-SPAS missions.

The Technology Applications and Science experiments, Manipulator Flight Demonstration supplied by Japan, and international Extreme Ultraviolet Hitchhiker were other mission payloads. The crew also worked with the Orbiter Space Vision System (OSVS), which would be used during ISS assembly. The OSVS featured a series of dots strategically placed on various payload and vehicle structures that permitted precise alignment and pointing capability. See Table 3–110 for further mission details.

STS-86

This mission launched September 25 and landed October 6, 1997, at Kennedy Space Center. It was the seventh docking between *Atlantis* and the *Mir* space station and the fourth exchange of U.S. astronauts. U.S. astronaut J. Michael Foale returned to Earth aboard *Atlantis* after a stay of 134 days on *Mir* and 145 days in space. His stay on *Mir* was the second longest spaceflight in U.S. history behind Shannon Lucid's 188-day flight in 1996. Foale was replaced by David Wolf.

The first joint U.S.-Russian EVA during a Shuttle flight took place on this mission. During a 5-hour, 1-minute spacewalk on October 1, Vladimir Titov and Scott Parazynski affixed a 121-pound (55-kilogram) Solar Array Cap to the docking module for future use by *Mir* crew members to seal off the suspected leak in Spektr's hull.[89] Parazynski and Titov also retrieved four MEEPs from the outside of *Mir* and tested several components of the SAFER jet packs.

Atlantis carried the SPACEHAB double module to support the transfer of logistics and supplies to *Mir* and the return of experiment hardware and specimens to Earth (see Figure 3–41). More than 4 tons (3,628 kilograms) of materials were transferred between SPACEHAB and *Mir*, including approximately 1,700 pounds (771 kilograms) of water; experiment hardware for ISS Risk Mitigation Experiments to monitor the *Mir* for crew health and safety; a gyrodone; batteries; three pressurization units with breathing air; an attitude control computer; and many other items. See Table 3–111 for further mission details.

STS-87

This mission launched November 19 and landed December 5, 1997, at Kennedy Space Center. It was the first time since 1992 that eight Shuttle flights were conducted in one year. The mission carried the USMP-4 and the SPARTAN 201-04 satellite as the primary payloads. It included experiments that studied how the weightless environment of space affected various physical processes. During this mission, payload specialist Leonid Kadenyuk became the first Ukrainian to fly aboard the Space Shuttle. Six minutes into the climb to orbit, *Columbia*'s computers commanded the orbiter to roll from an inverted position under its fuel tank to a "heads-up" position to provide early communications access to the TDRS system. That enabled NASA to phase out the Bermuda tracking station to save costs to the Shuttle program.

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[89] The accident that caused the leak is described later in this chapter.

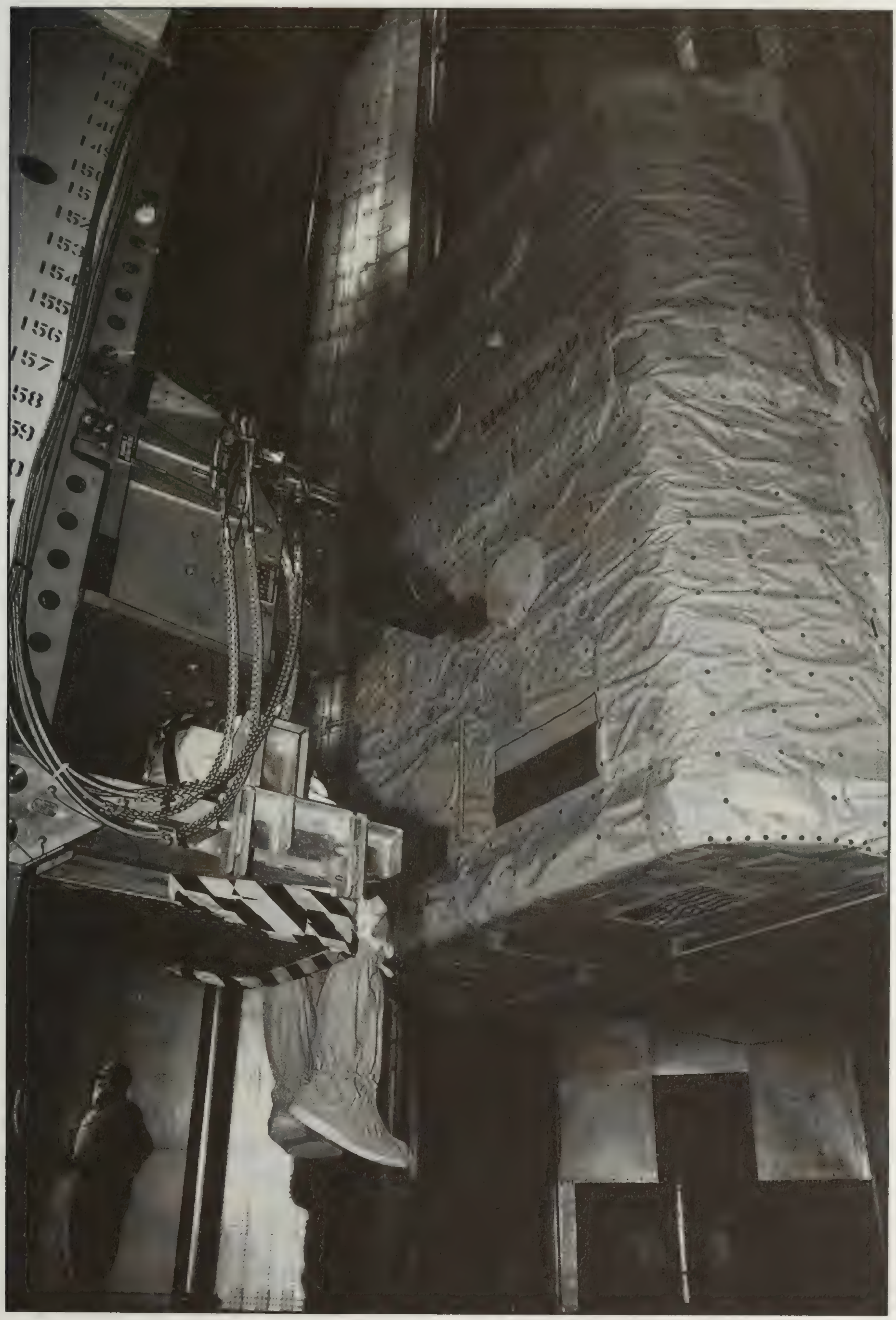

Figure 3–41. The SPACEHAB double module is lifted into the payload changeout room at Launch Pad 39-A for insertion into the payload bay of Atlantis. *On STS-86, about 3-1/2 tons (3,175 kilograms) of science and logistical equipment and supplies were exchanged between* Atlantis *and* Mir. *(NASA Photo No. KSC-97PC-1340)*

An unexpected event occurred when the attitude control system aboard the free-flying SPARTAN solar research satellite malfunctioned, causing the satellite to rotate outside the Shuttle. After unsuccessful attempts to capture the satellite using the orbiter's mechanical arm, crew members performed an unscheduled spacewalk lasting 7 hours, 43 minutes, successfully recapturing the satellite and lowering it onto its berth in the payload bay manually. The anomaly prevented all planned research on SPARTAN from being performed. A second spacewalk lasting 7 hours, 33 minutes tested a crane to be used for constructing the ISS and a free-flying camera to monitor conditions outside the Station without requiring EVAs. See Table 3–112 for further mission details.

STS-89

This mission launched January 22 and landed January 31, 1998, at Kennedy Space Center. The eighth *Mir*-Shuttle linkup and the fifth crew exchange took place. Astronaut David Wolf, who had been on *Mir* since September 1997 and had spent 128 days in space, was replaced by astronaut Andrew Thomas. In addition to using the SPACEHAB Logistics Double Module to supply *Mir* with more than 8,000 pounds (3,629 kilograms) of scientific equipment, logistical hardware, and water, the mission recovered the Optical Properties Monitor from *Mir*. This important experiment exposed material samples composed mostly of optical instruments and coatings to space conditions. See Table 3–113 for further mission details.

STS-90

This mission launched April 17 and landed May 3, 1998, at Kennedy Space Center. This was the 23rd and final Spacelab module flight, which had spanned the prior 15 years. The key science focused on Neurolab, a set of investigations relating to the effects of microgravity on the nervous system. The experiments studied vestibular system adaptation and space adaptation syndrome, adaptation of the central nervous system and the pathways that control the ability to sense location and orientation in the absence of gravity, and the effect of microgravity on a developing nervous system (Figure 3–42).

The mission was a joint venture of six space agencies and seven U.S. research agencies. Investigator teams from nine countries conducted 31 studies in the microgravity environment of space. The agencies participating in this mission included six institutes of the National Institutes of Health, the National Science Foundation, and the Office of Naval Research, as well as the space agencies of Canada, France, Germany, Japan, and the ESA. See Table 3–114 for further mission details.

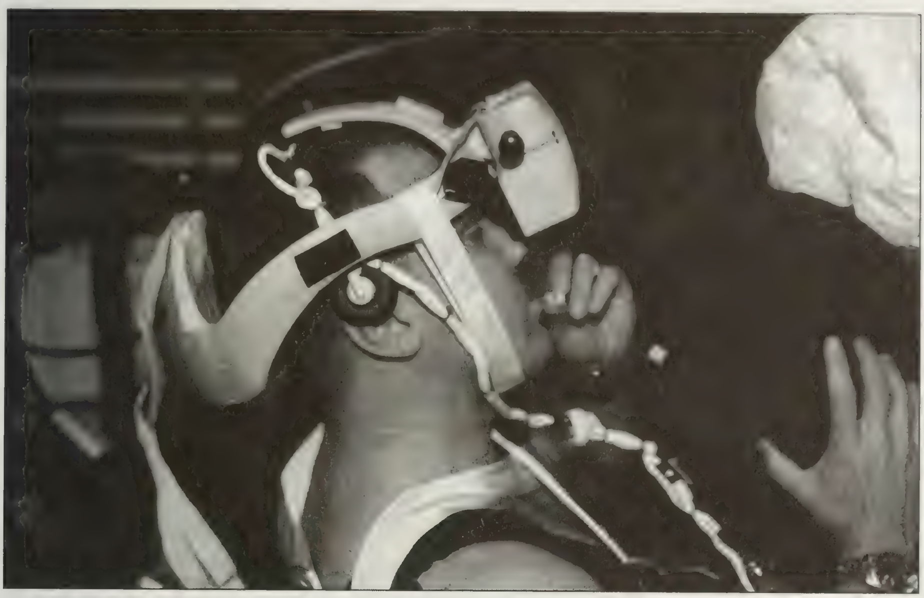

Figure 3–42. This Electronic Still Camera (ESC) image shows Dafydd R. "Dave" Williams, Mission Specialist, working with the Virtual Environment Generator (VEG), in the Neurolab on board Columbia, *on April 20, 1998. The VEG was used to discover how the balance between visual and vestibular cues shifts toward the visual system in weightlessness. The VEG was a head-mounted display that showed computer-generated virtual reality scenes generated by a three-dimensional graphics computer. (NASA Photo No. STS90-E-5041)*

STS-91

This mission launched June 2 and landed June 12, 1998, at Kennedy Space Center. It was the ninth and last *Mir* docking mission. It was the first docking mission for *Discovery.* Astronaut Andrew Thomas returned to Earth after completing 130 days of living and working on *Mir.* No U.S. astronaut was delivered to *Mir.* Thomas' transfer ended a total of 907 days spent by seven U.S. astronauts aboard the Russian space station as long-duration crew members.

Discovery carried the single SPACEHAB module in its payload bay. The module housed experiments performed by the astronauts and served as a cargo carrier for the items transferred to *Mir* and returned to Earth.[90] During the docked phase of STS-91, astronauts and cosmonauts transferred more than 1,100 pounds (500 kilograms) of water, and almost 4,700 pounds (2,132 kilograms) of cargo experiments and supplies were exchanged between the two spacecraft.

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[90] *Mir* remained in orbit until March 23, 2001, when it returned to Earth after 86,331 total orbits. Five of *Mir's* modules were still pressurized at the time of deorbit and burst into flame as fragments fell into the South Pacific Ocean as ground controllers had planned. (Roger D. Launius, *Space Stations, Base Camps to the Stars* (Washington, DC: Smithsonian Institution, 2003), pp. 172–173. Between the final Shuttle-*Mir* docking and June 2000, the station remained crewed by Russian cosmonauts. In January 2001, a Progress cargo vehicle was launched in preparation for its March docking and deorbit of *Mir.* "Mir Chronicles," *http://www.russianspaceweb.com/mir_chronology.html* (accessed November 29, 2005). Also "Mir Space Station Observing," *http://satobs.org/mir.html* (accessed November 29, 2005).

STS-91 also carried into space the Alpha Magnetic Spectrometer (AMS) Investigation. The objectives of this investigation were to search for anti-matter and dark matter in space and to study astrophysics.

The mission was the first use of the super lightweight external tank (SLWT). This new tank was the same size, 154 feet long and 27 feet in diameter, (47 meters by 8.2 meters) as the external tank used on previous Shuttle launches but 7,500 pounds (3,401 kilograms) lighter. It was made of an aluminum lithium alloy, and the structural design had been improved, making the SWLT 30 percent stronger and 5 percent less dense. The walls of the redesigned hydrogen tank were machined in an orthogonal, waffle-like pattern, providing more strength and stability than the previous design. These improvements made additional payload capacity available to the ISS. See Table 3–115 for further mission details.

STS-95

This mission launched October 29 and landed November 7, 1998, at Kennedy Space Center. The mission conducted a variety of science experiments in the pressurized SPACEHAB module, deployed and retrieved the SPARTAN free-flyer payload, and carried out operations with the Hubble Space Telescope Orbiting Systems Test (HOST) and the IEH payloads in the payload bay. This mission was dubbed "the John Glenn Mission" because of its famous crew member. The scientific research mission returned space pioneer John Glenn to orbit 36 years, 8 months, and 9 days after he became the first American to orbit Earth. A battery of tests on Glenn and Pedro Duque furthered research on how the absence of gravity affected balance, perception, immune system response, bone and muscle density, metabolism and blood flow, and sleep.

The HOST provided a unique opportunity to test key pieces of new Hubble Space Telescope hardware before installation on future servicing missions. By flying the Shuttle in an orbit similar to Hubble Space Telescope's, the HOST allowed engineers to determine how the new equipment would perform on the telescope. HOST engineers monitored the effects of radiation on Hubble Space Telescope's new hardware, including an advanced computer, digital data recorder, and cryogenic cooling system. All the new technologies on the HOST mission performed as expected.

The SPARTAN spacecraft investigated physical conditions and processes of the hot outer layers of the Sun's atmosphere, or solar corona. While deployed from the Shuttle, SPARTAN gathered measurements of the solar corona and solar wind. This was a reflight of the SPARTAN payload flown on STS-87 that had developed problems soon after deployment from the Shuttle. See Table 3–116 for further mission details.

STS-88

This mission, the last in the 1989–1998 decade, launched December 4 and landed December 15, 1998, at Kennedy Space Center. This mission marked the start of ISS assembly when the U.S. module Unity mated with the Russian Zarya module that had been launched by a Proton rocket on November 20.[91] Astronauts Jerry Ross and James Newman conducted three spacewalks to attach cables, connectors, and hand rails. The two modules were powered up after the astronauts' entry.

Ross and Newman met other EVA objectives as they tested a SAFER unit, a self-rescue device to aid a spacewalker who becomes separated from the spacecraft during an EVA. They also nudged two undeployed antennas on Zarya into position; removed launch restraint pins on Unity's four hatchways for mating future additions of Station modules and truss structures; installed a sunshade over Unity's two data relay boxes to protect them from harsh sunlight; stowed a tool bag on Unity and disconnected umbilicals used for the mating procedure with Zarya; installed a handrail on Zarya; and made a detailed photographic survey of the Station.

Astronauts completed assembly of an early S-band communications system that allowed flight controllers in Houston to send commands to Unity's systems and keep tabs on the health of the Station, and conducted a successful test of the videoconferencing capability of the early communications system that the first permanent crew would use. Astronauts Sergei Krikalev and Nancy Currie also replaced a faulty unit in Zarya.

A new spacewalk record was established as Ross completed his seventh walk, totaling 44 hours, 9 minutes. Newman moved into third place with four EVAs totaling 28 hours, 27 minutes. See Table 3–117 for further mission details.

Space Station

Overview[92]

The Space Station is the largest and most complex international scientific project in history. Space Station development began in 1984 with President Ronald Reagan's call to create a permanent human presence in space. Called *Freedom* in its early planning stages, *Alpha* in 1993, and finally the ISS, assembly began in 1998 with the launch of the first two components, the Unity and Zarya modules. Led by the United States, the ISS has drawn upon the scientific and technological resources of 16 nations: Canada, Japan, Russia, 11 ESA member nations, and Brazil. The United States is responsible for developing and ultimately operating the major elements and systems aboard the Station. Beginning in 1993, Russia has been a prime partner in Space Station development, contributing both Space Station elements and knowledge gleaned from years of long-duration spaceflight.

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[91] "Zayra" means "sunrise." See the section describing Space Station development later in this chapter for more details of this mission.

[92] Most material in the overview came from "The International Space Station: An Overview," *NASA Facts,* IS-1999-06-ISS022, June 1999, *http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/issovw.pdf* (accessed June 28, 2005).

The completed ISS, as configured in 1999, will have a mass of about 1 million pounds (453,592 kilograms), more than four times as large as the Russian *Mir* space station. It will measure about 360 feet (110 meters) across and 290 feet long (88 meters), with almost an acre of solar panels to provide electrical power to six laboratories. The first two ISS modules, the Russian-launched Zarya control module and the U.S.-launched Unity connecting module, were assembled in orbit in late 1998. This orbiting two-module complex had a mass of more than 74,000 pounds (33,566 kilograms) and measured 76 feet long (23 meters) with a 78-foot (23.8-meter) wingspan of the solar arrays. The Station's internal pressurized volume was 4,635 cubic feet (131.2 cubic meters). By early 1999, about 500,000 pounds (226,796 kilograms) of Station components had been built at factories around the world.

The ISS orbits at an altitude of 250 statute miles (402 kilometers) with an inclination of 51.6 degrees. This orbit allows launch vehicles of all the international partners to reach the Station, providing the capability to deliver crews and supplies. The orbit also allows excellent Earth observations with coverage of 85 percent of the globe and overflight of 95 percent of the population.

The program was organized into three phases since it became the ISS. The first phase of the ISS, the Shuttle-*Mir* program, began in 1995 and involved more than two years of continuous stays by U.S. astronauts on *Mir* and nine Shuttle-*Mir* docking missions. Seven U.S. astronauts spent a cumulative total of 32 months aboard *Mir* with 28 months of continuous occupancy since March 1996. By contrast, it took the U.S. Space Shuttle fleet more than 12 years and 60 flights to achieve an accumulated one year in orbit.

The knowledge and experience NASA gained through the Shuttle-*Mir* program could not have been achieved in any other way. NASA acquired valuable skills in international crew training activities; operating an international space program; and meeting the challenges of long-duration spaceflight for astronauts and ground controllers. Dealing with the real-time challenges encountered during Shuttle-*Mir* missions also resulted in unprecedented cooperation and trust between members of the U.S. and Russian space programs that has enhanced ISS development.

Many of the research programs planned for the ISS benefit from longer times in space. It is envisioned that research in the Station's six laboratories will lead to discoveries in medicine, materials, and fundamental science that will benefit people around the world. Through its research and technology, the ISS also will serve as an indispensable step in preparing for future human space exploration.

See Table 3–131 for a chronology of Space Station development.

ISS Partners

A worldwide team consisting of the United States, Canada, ESA, Japan, Russia, Italy, and Brazil is providing components for the ISS.

The United States, through NASA, is the initiator, integrator, and leader of the ISS effort. The United States is contributing the truss structures making up the Station's framework; four pairs of large solar arrays; three connecting modules, or nodes, with ports for spacecraft and for passage to other ISS elements; a cupola; an unpressurized logistics carrier; and an airlock accommodating U.S. and Russian spacesuits. NASA is also furnishing laboratory, habitation, and centrifuge accommodation modules.

NASA's integrated services include thermal control; power; environmental control and life support; communications, tracking, and data handling services; guidance, navigation, and control; and crew health maintenance as well as ground operations and launch site processing facilities.

Canada's CSA is providing the Mobile Servicing System, a 55-foot (16.8-meter), 125-ton (113,398-kilogram)-capacity robotic arm called the Space Station Remote Manipulator System (SSRMS), as well as a 12-foot (3.7-meter) Special Purpose Dexterous Manipulator (SPDM) arm. The Mobil Servicing System will aid in ISS assembly and maintenance. Canada will also supply the Space Vision System, a Shuttle-tested advanced camera to assist astronauts in viewing the SSRMS.

The European Space Agency comprises Belgium, Denmark, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, and the United Kingdom. The ESA is providing the Columbus Orbital Facility to be launched on the Ariane 5 expendable launch vehicle and the Automated Transfer Vehicle. The ESA was cooperating on development of the X-38 Crew Return Vehicle (canceled in 2002).

The Columbus Orbital Facility will carry 10 refrigerator-size racks for holding experiments, half of them European research projects. The Automated Transfer Vehicle will be used for logistics and propellant resupply as well as for reboost of the ISS.

Japan's National Space Development Agency is providing the Japanese Experiment Module. This experiment module houses the pressurized module, Exposed Facility, a remote manipulator system, and an Experiment Logistic Module. The pressurized module comprises a laboratory to accommodate 10 racks for holding experiments. The Exposed Facility is an external platform for up to 10 unpressurized experiments in the vacuum of space.

The 32-foot (9.8-meter) remote manipulator system will be used for servicing the Exposed Facility system and for changing payloads. The Experiment Logistic Module will be used for pressurized and unpressurized logistics resupply missions.

The Russian Space Agency is supplying about one-third the mass of the ISS in the form of a service module, Universal Docking Module, Science Power Platform, Docking Compartment, and research modules. The service module provides early living quarters for ISS crews, while the Universal Docking Module provides docking for both Russian and U.S. space vehicles. The Russian Space Agency provides crew transfers on the Soyuz and logistics resupply, Station reboosting, and orientation adjustments with its Progress and other vehicles. Russia built the first ISS element launched into orbit, the U.S.-funded Zarya.

Italy is participating as part of the ESA as well as independently providing three Multi-Purpose Logistics Modules through the ASI. The modules will be used on the Shuttle to carry pressurized cargo and payloads to the ISS. The structural design of the modules forms the basis for the design of the ESA's Columbus Orbital Facility. The agency also will supply Nodes 2 and 3 to NASA.

The Instituto Nacional de Pesquisas Espaciais (INPE) in San Jose dos Campos, Brazil, will provide six items under the direction of the Brazilian Space Agency, Agencia Espacial Brasileira (AEB). These constitute attachment devices and a pallet on which experiments and equipment will ride in Shuttle missions to the ISS. Brazil's Technology Experiment Facility will provide long-term space exposure for selected experiments, while Window Observation Research Facility 2 will be devoted to observation and remote sensing development.

Background

In January 1984, in his State of the Union address, President Ronald Reagan called for NASA "to develop a permanently manned space station and to do it within a decade."[93] From that day on, NASA committed to building a Space Station, then with a 1994 completion date on the calendar. The Agency created the necessary organizational structure and began work on the baseline concept. NASA stated in April 1988 that "the Space Station is essential if the United States is to maintain preeminence in key areas of civil space activities during the 1990s and beyond."[94] By the end of 1988, President Ronald Reagan had named the orbiting structure *Freedom*; and NASA had formed an international partnership with nine European nations; Canada; and soon Japan; as well as their respective space agencies; the ESA; the CSA; and Japan's NASDA. These alliances pledged cooperation during the detailed design, development, and operation and utilization phases of the Space Station program and agreed to provide the components of this modular orbiting laboratory.

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[93] "State of the Union Message, January 25, 1984," *Public Papers of the Presidents of the United States: Ronald Reagan, 1984* (Washington, DC: Government Printing Office, 1986), pp. 87–95.

[94] Office of Space Station, National Aeronautics and Space Administration, "Space Station Capital Development Plan, Fiscal Year 1989," Submitted to the Committee on Science, Space and Technology, U.S. House of Representatives and the Committee on Commerce, Science and Transportation, U.S. Senate, April 1988, p. 1.

At the same time, NASA chose its prime contractor team of Boeing Aerospace, McDonnell Douglas, General Electric, and the Rocketdyne Division of Rockwell International for the implementation and execution phases, hardware development, and advanced design. NASA awarded four 10-year contracts with a total value of approximately $6.7 billion to correspond to the four "work packages" centered at four NASA Centers: Marshall Space Flight Center, Johnson Space Center, Goddard Space Flight Center, and Lewis Research Center. The Station was considered a facility that would "allow evolution in keeping with the needs of Station users and the long-term goals of the United States."[95]

Since 1987, the Station had been planned for completion in two phases. Phase I, known as the "revised baseline configuration," included a single horizontal boom, U.S. laboratory and habitat modules, accommodation for attached payloads, U.S. and European polar platforms, 75 kilowatts of photovoltaic power, European and Japanese laboratory modules, the Canadian Mobile Servicing System, and provisions for evolution. An earlier structural configuration, consisting of a dual keel with additional accommodations for attached payloads, had been moved to Phase II, known as the "enhanced configuration." Under the 1987 plan, the dual keel would be added only when support requirements of the attached payloads exceeded the capacity of the original solar panel truss. NASA had changed from the earlier single-phase, dual-keel plan to two phases because planners doubted that the Space Shuttle could schedule enough flights within the available time to deliver the truss elements needed for a dual keel.[96] Phase II also included an additional 50 kilowatts of power from the solar dynamic system, the satellite servicing facility, and the U.S. co-orbiting laboratory satellite.[97] NASA also decided to give the Station a "man-tended" status in Phase I and upgrade to "permanent habitability" after Phase I was complete.[98] Phase II was initially planned for sometime after the 20th assembly flight in early 1998, but it never received funds and was postponed indefinitely. Table 3–118 shows the Phase I and II contractors, tasks, and contract values.

Space Station Freedom

Space Station *Freedom* development did not proceed smoothly. Congress balked at the rising cost, which by 1987 had grown by more than 80 percent to $14.5 billion in FY 1984 dollars.[99] NASA also slipped the goal of a permanently occupied Space Station, as stated by President Ronald Reagan, to 1995 and the assembly completion date from 1994 to early 1997.[100] Support by the science community also was uneven as some questioned the value of the Station for scientific research and worried that money spent on *Freedom* would reduce the amount available for other scientific pursuits. Consequently, Space Station *Freedom* was redesigned several times in an effort to reduce the price and streamline construction.

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[95] "Fact Sheet, Presidential Directive on National Space Policy, February 11, 1988," (actual policy statement was classified), *http://www.fas.org/spp/military/docops/national/policy88.htm* (accessed March 1, 2005).

[96] David M. Harland and John E. Catchpole, *Creating the International Space Station* (Chichester, UK: Springer-Praxis Books, 2002), p. 118.

[97] U.S. General Accounting Office, *Space Station: NASA's Search for Design, Cost, and Schedule Stability Continues,* GAO/NSIAD-91-125, March 1991, p. 23, *http://archives.gao.gov/d21t9/143481.pdf* (accessed June 1, 2005).

[98] Man-tended referred to short-term occupation of the Station while a Shuttle orbiter or Soyuz was docked at the Station. Permanent habitability meant a continuous presence on the Station.

[99] Launius, pp. 134–136.

Congress kept tight control over Space Station funding, insisting that NASA request funds annually rather than appropriate funds the project could use over several years. This forced NASA to repeatedly justify the Station's cost, causing increased friction between NASA and Congress. In 1988, when introducing the FY 1990 budget request, NASA Administrator James Fletcher stated that the proposed cost was as low as possible and there was no room for further reductions. Congress still was unwilling to provide adequate funding, and Fletcher resigned on April 8, 1989. Dale Meyers, Fletcher's deputy, briefly became Administrator until the President appointed Richard Truly later in the year. In June, James Odom, Space Station program head only since March 1988, retired, and Truly appointed former astronaut William Lenoir to the job. Lenoir was also given the task of working out the consolidation of the Office of Space Station and Office of Space Flight, the organization managing the Space Shuttle.

As of April 1989, Space Station *Freedom* was planned as a 476-foot (145-meter) main truss assembly. Components included:

- A U.S. laboratory module
- A habitation module that would allow a continuous human presence
- A European attached pressurized module
- A Japanese experiment module
- Four resource nodes
- One standard and one hyperbaric airlock
- A logistics carrier
- A flight telerobotic servicer
- A Canadian mobile servicing system
- Attached payload accommodations equipment
- A propulsion assembly

The laboratories would provide for extensive science, applications, and technology development. There would also be provisions for external attached payloads, and three additional free-flyer spacecraft would be provided.[101]

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[100] U.S. General Accounting Office, *Space Station: NASA's Search for Design, Cost, and Schedule Stability Continues,* GAO/NSIAD-91-125, March 1991, p. 21, *http://archive.gao.gov/d21t9/143481.pdf* (accessed 1 June 2005).

[101] National Aeronautics and Space Administration, Office of Space Station, *Space Station Freedom Capital Development Plan, Fiscal Year 1990,* April 1989, pp. 12–27 (NASA History Office Folder 009508).

This configuration did not survive. First, in June 1989, NASA began overhauling the Space Station assembly sequence. It decided to rely only on the current Space Shuttle capabilities for lifting and assembling Station components. The Agency abandoned the possibility of a Shuttle advanced solid rocket motor to increase the Shuttle's carrying capacity as well as the availability of an orbital maneuvering vehicle or a Shuttle-C vehicle.[102] Phase II was postponed indefinitely, and the polar platform transferred from the Space Station program to NASA's Office of Space Science and Applications for use in Earth observation studies.

Next, in July 1989, NASA formed a Configuration Budget Review team headed by W. Ray Hook of Langley Research Center. The team established three control boards that meticulously reviewed the program to develop preliminary options for ways the program could exist within the severe budget constraints threatened by Congress. The team presented these options to NASA Space Station management and the international partners.[103]

Based on this major program review, NASA announced late in 1989 a "rephasing" of the program to meet an anticipated budget cut of nearly $300 million for FY 1990 and "to reduce technical, schedule, and cost risk."[104] (Congress had in the meantime passed a FY 1990 funding bill in October 1989 to fund the Space Station program at $1.8 billion, $250 million less than the administration's $2.05 billion budget request.) Major program modifications included:

- Swapping the hydrogen-oxygen attitude control thrusters for more conventional hydrazine thrusters requiring little development cost.
- Eliminating a completely closed-loop environmental system that recycled *Freedom*'s water and air supply, instead shipping supplies to *Freedom* from Earth on the Shuttle.
- Rearranging the module layout to eliminate several interconnecting node modules.
- Eliminating two airlocks that would have provided redundancy and storage space for spacesuits and other EVA equipment and replacing them with a single airlock with hyperbaric treatment capability for treating decompression sickness.
- Eliminating two deployable booms that would have held the propulsion system and the communications and tracking antennas and adding two truss bays below the standard truss to hold that equipment, one on each end.

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[102] The orbital maneuvering vehicle was planned as a reusable, remotely controlled free-flying "space tug." The Shuttle-C vehicle was a heavy-duty, uncrewed, Shuttle-like hauler of cargo.

[103] Harland and Catchpole, p. 122.

[104] "NASA Officials Make Some Changes to Space Station Freedom To Reduce Risk," *Station Break* 2, no. 1 (January 1990) (NASA History Office Folder 009522).

- Reducing the number of attachment fixtures for external payloads and utilities.[105]
- Scrapping development of new high-pressure spacesuits, leaving the crew with existing suits used for Shuttle EVA.[106]

These changes kept the first element launch scheduled for March 1995 but delayed the assembly complete date by 18 months. Figure 3–43 shows the proposed configuration for the completed Space Station as of 1991.

The various modules had been determined early in *Freedom*'s development. These remained in place throughout the various modifications that followed. The module cluster consisted of the U.S. laboratory and habitation modules, the ESA's attached pressurized module, and the Japanese Experiment Module.

The U.S. laboratory module (see Figure 3–44) was a pressurized, shirt-sleeve laboratory containing racks to house experiments and *Freedom*'s systems. The racks were a standard size (approximately as large as a refrigerator) to simplify replacement and for commonality with the racks in the other laboratory modules to be delivered later in the assembly. Of the 24 racks in the U.S. lab, 15 were allotted to the users to perform research and development activities. The remaining nine racks were for *Freedom*'s systems, such as the environmental control system and guidance and navigation systems. The U.S. habitation module (see Figure 3–45) served as living quarters for *Freedom*'s crew. It provided room for relaxation, personal hygiene, and exercise, as well as on-board medical facilities.

The attached pressurized module from the ESA (see Figure 3–46) and the Japanese Experiment Module laboratories (see Figure 3–47) provided 20 and 10 user racks, respectively, enabling investigations into material properties, fluid dynamics, and the behavior of living organisms in a weightless environment. The attached pressurized module provided a shirt-sleeve environment for astronauts and was equipped with power supply, thermal control, environmental control and life support, and data handling systems. The Japanese Experiment Module also provided a pressurized shirt-sleeve environment for astronauts and was equipped with power supply, thermal control, environmental control and life support, and data handling systems. An external platform, called the Exposed Facility (see Figure 3–48) would be attached to the rear of the Japanese Experiment Module. This facility provided additional attach ports for external payloads. The Japanese Experiment Module's robotic arm could replace or service payloads on the Exposed Facility.

The SSRMS and the SPDM were Canada's contribution to Space Station *Freedom* (see Figure 3–49). The SPDM had two 6-foot (1.8-meter) robotic arms for delicate tasks, such as connecting and disconnecting utilities, exchanging orbital replacement units, and assisting in Space Station assembly, maintenance, and repair activities. The SSRMS and the SPDM, together with the mobile transporter, made up the Mobile Servicing System. This system had lighting and video capabilities to assist astronauts in remote handling and visual inspection of payloads.

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[105] Billie Deason, "Budget-Minded Changes Alter Freedom Plans," *Space News Roundup*, NASA Johnson Space Center (April 27, 1990): 3 (NASA History Office Folder 009523).

[106] Robert Zimmerman, *Leaving Earth; Space Stations, Rival Superpowers, and the Quest for Interplanetary Travel* (Washington, DC: Joseph Henry Press, 2003), p. 222.

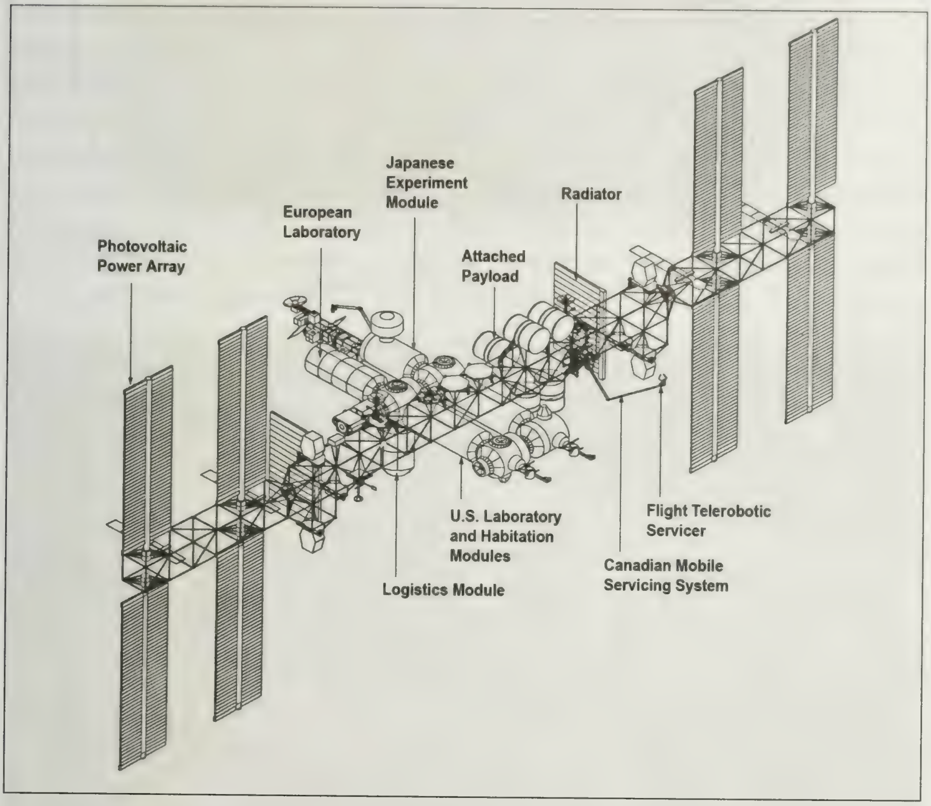
Japanese Experiment Module
Radiator
European Laboratory
Photovoltaic Power Array
Attached Payload
U.S. Laboratory and Habitation Modules
Flight Telerobotic Servicer
Canadian Mobile Servicing System
Logistics Module

Figure 3–43. Space Station Freedom *Configuration, 1991. (NASA History Office Folder 009524)*

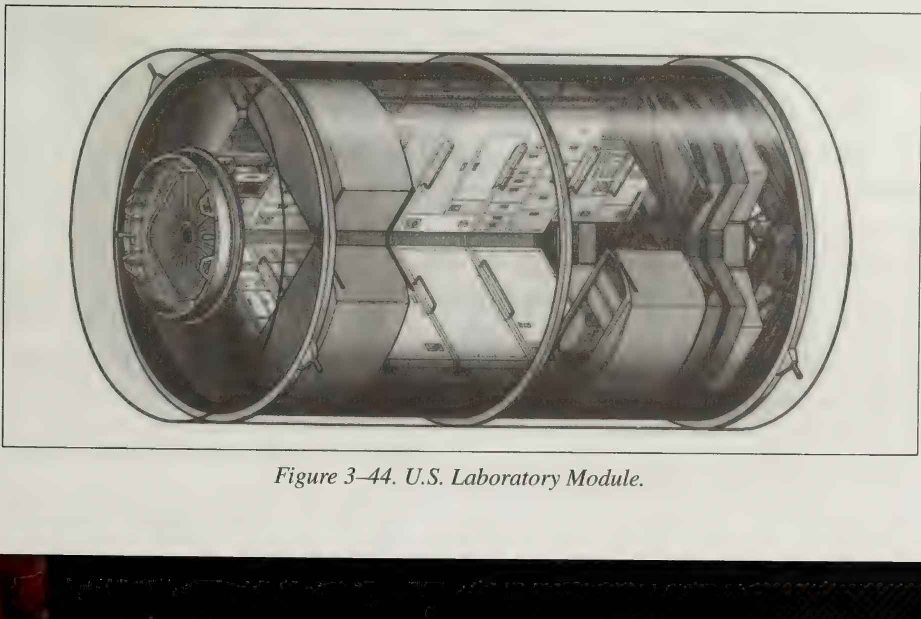

Figure 3–44. U.S. Laboratory Module.

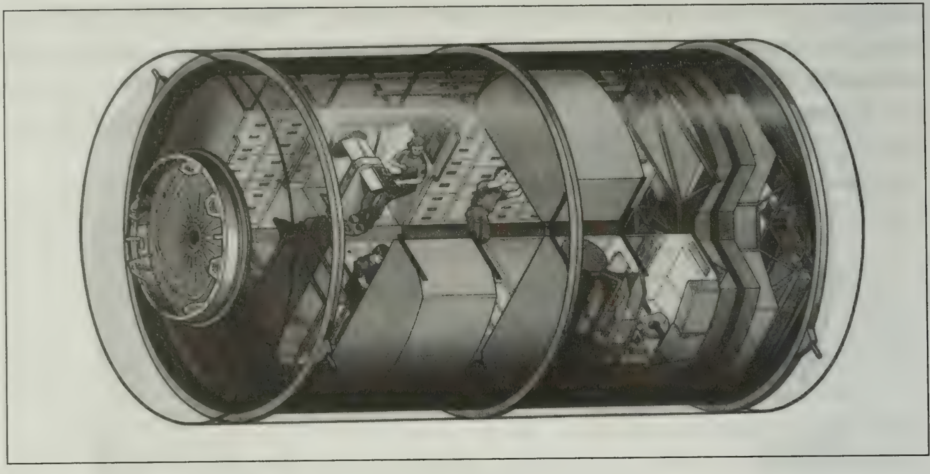

Figure 3–45. U.S. Habitation Module.

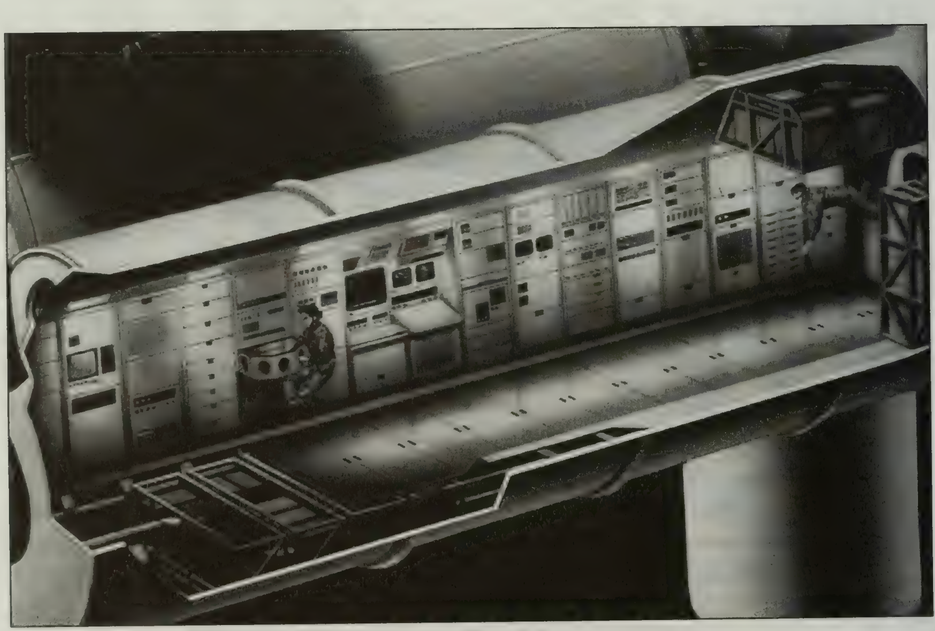

Figure 3–46. The ESA Attached Pressurized Module.

NASA and the White House continued to look for ways to reconfigure the Station to cut costs, forming advisory groups and teams to look at alternatives and propose recommendations. In January 1990, NASA formed the External Maintenance Task Team (EMTT) to address concerns about the number of spacewalks needed to maintain the Station. The team recommended significantly reducing annual EVA. A complementary team formed in June 1990, the External Maintenance Solutions Team, addressed problems raised by the EMTT and made further recommendations for reducing EVA maintenance.[107]

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[107] *Space Station Freedom Media Handbook,* 1992, pp.18–19.

In the fall of 1990, the White House formed the Advisory Committee on the Future of the U.S. Space Program, chaired by Norman Augustine, to "assess alternative approaches and make recommendations for implementing future civil space goals" and to advise the NASA Administrator on overall approaches to implement the U.S. space program. The Committee had 120 days to make "a serious no-holds-barred" review of the space program and recommend improvements.[108] The Committee recommended that "steps should be taken to reduce the Station's size and complexity, permit greater end-to-end testing prior to launch, reduce transportation requirements, reduce extra-vehicular assembly and maintenance, and, where it can be done without affecting safety, reduce cost." The Committee also recommended revamping the program to emphasize life sciences and human space operations, including microgravity research as appropriate. Although Congress had given NASA only 90 days to "implement a revised space station design and assembly sequence," the Committee stated that this might prove inadequate and as much time as needed should be taken. The Committee also strongly recommended the immediate availability of a crew rescue vehicle.[109]

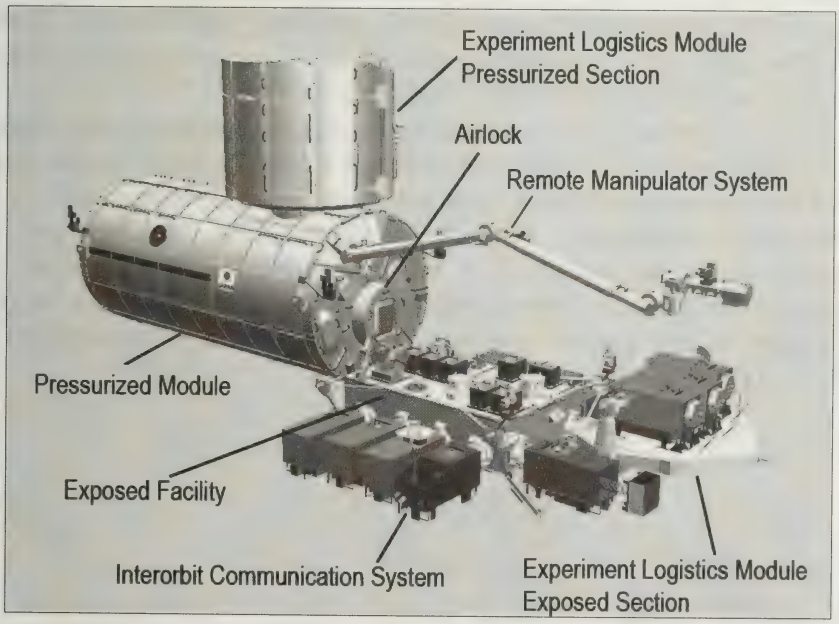
Experiment Logistics Module
Pressurized Section
Airlock
Remote Manipulator System
Pressurized Module
Exposed Facility
Interorbit Communication System
Experiment Logistics Module
Exposed Section

Figure 3–47. Japanese Experiment Module.

NASA seriously considered the reviews, recommendations, and direction from Congress, delivering to Congress in March 1991 a restructuring report laying out an extensively redesigned Station. It had a $30 billion price tag

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[108] Harland and Catchpole, p. 124.

[109] Advisory Committee on the Future of the U.S. Space Program, "Report of the Advisory Committee on the Future of the U.S. Space Program, December 1990," *http://www.hq.nasa.gov/office/pao/History/augustine/racfup1.htm* (accessed March 15, 2005).

(including launches) but was smaller, easier to assemble in orbit, and would require fewer Shuttle flights to build.[110] The number of crew members on board was reduced from eight to four and the flight telerobotic servicer (FTS) was moved from the Space Station program to NASA's Office of Aeronautics, Exploration, and Technology. One large solar panel on *Freedom* was eliminated, reducing the panel's power from 75 kilowatts to 35 kilowatts. Following Congress's instructions for components that could be built in stages, the main truss was shortened to 353 feet (108 meters) and modified so it could be pre-integrated and tested with all subsystems before launch, reducing the EVA time needed to build and maintain the Station. The U.S. laboratory and habitation modules were shortened by 40 percent and also could be built, preassembled, and checked out on the ground. Because of the shortened truss, the facilities for large attached payloads were no longer needed and were canceled, although the hardpoints on the truss would still be used for small payloads. The cancellation of the FTS and the attached payload accommodation equipment eliminated Work Package 3, and NASA terminated its contract with GE Astro.[111] The schedule was also rephased. The first element launch was moved to early 1996. Man-tended capability was delayed until mid-1997, when docked Shuttles would be able to use *Freedom* for periods of up to two weeks. Permanent occupation was postponed for three years until 2000.[112]

This redesign was poorly received by the science community and NASA's international partners. The National Research Council's Space Studies Board stated that the redesign did not "meet the basic research requirements" for life sciences and microgravity research and applications, "the two principal scientific disciplines for which it is intended."[113] The modifications also displeased the Station's international partners both because of the delay in deployment of their modules and because they had not been consulted on the changes, a violation of their agreements.

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[110] *Space Station Freedom Media Handbook*, 1992, p. 19. Also Marcia S. Smith, Congressional Research Service, testimony to the Science Committee, U.S. House of Representatives, "NASA's Space Station Program: Evolution and Current Status," 4 April 2001, *http://www.spaceref.com/news/viewsr.htm?pid-2562* (accessed June 3, 2005); also *http://www.house.gov/science/full/apr04/smith.htm* (accessed June 7, 2005).

[111] "Goddard Announces Contract Termination," *NASA News* Release 91-27, February 15, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-027.txt* (accessed March 22, 2005). The contract for the payload accommodation equipment also included two polar platforms to be used for on-orbit research as part of the EOS. A new contract for these items was drawn up with GE Astro.

[112] Peter Bond, *The Continuing Story of the International Space Station* (London: Springer-Praxis Books, 2002), p. 114.

[113] National Research Council, Commission on Physical Sciences, Mathematics, and Applications, "Space Studies Board Position on Proposed Redesign of Space Station Freedom," March 29, 1991 (NASA History Office Folder 009524).

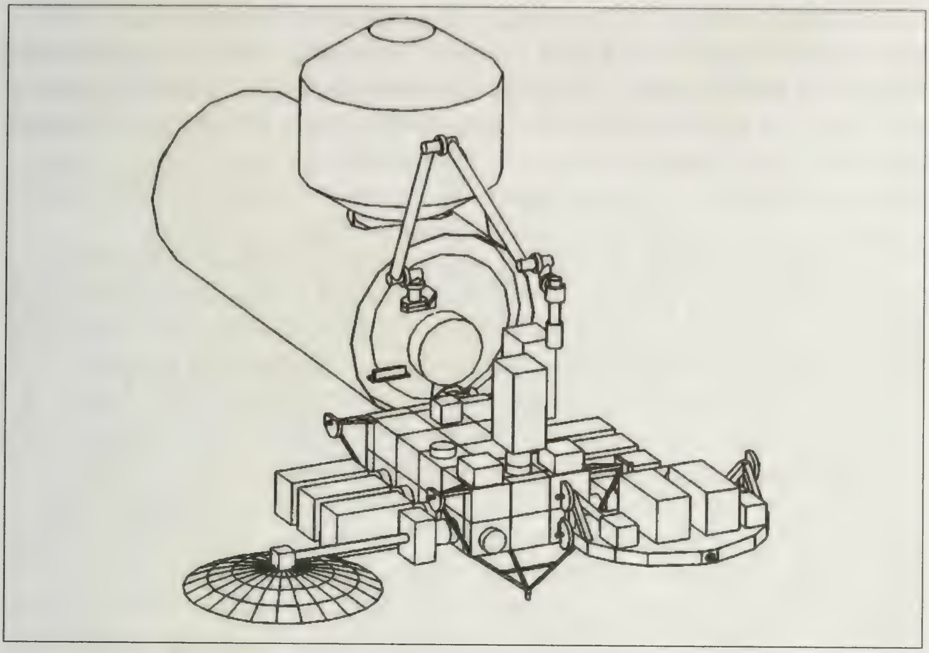

Figure 3–48. Japanese Experiment Module Exposed Facility.

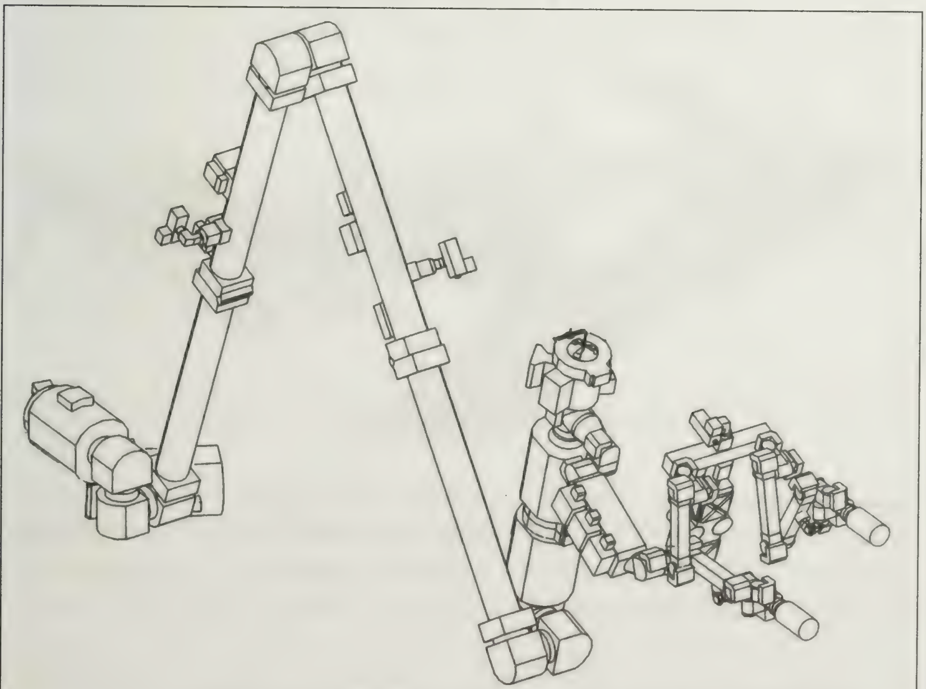

Figure 3–49. Canada's SPDM attached to the SSRMS.

Nevertheless, Vice President Dan Quayle and the National Space Council endorsed the report on March 21, 1991. After the House Appropriations Committee recommended cutting off all funding for *Freedom* and canceling it, the Senate, on September 27, 1991, agreed to the House bill and granted NASA its full FY 1992 funding request of $2,028,900,000 for Space Station *Freedom.* President George H. W. Bush signed the bill on December 9.[114] This vote to cancel the program was the first of many that the Station survived.

In spring of 1992, the NASA Space Station Freedom Office issued a strategic plan for the program.[115] The plan presented a "vision of what *Freedom* will accomplish, as well as its mission, goals, and objectives." The plan described the three-phase process with a separate "man-tended capability" and a "permanently manned capability." (See Figures 3–50 and 3–51). During the man-tended capability period, the crew would remain on-board *Freedom* only while the Space Shuttle was docked, returning to Earth with the Shuttle after each mission. The beginning of the permanently manned capability would be marked by the addition of the Assisted Crew Return Vehicle, to be added during 1999. Figure 3–52 shows the progression from Stage 1, first element launch, through Stage 6, man-tended capability, to Stage 17, permanently manned capability, as envisioned in July 1992. Assembly would take approximately four years, beginning in the fall of 1995 with the first element launch, and would require 18 mission build flights during that period to transport *Freedom*'s components into orbit.[116]

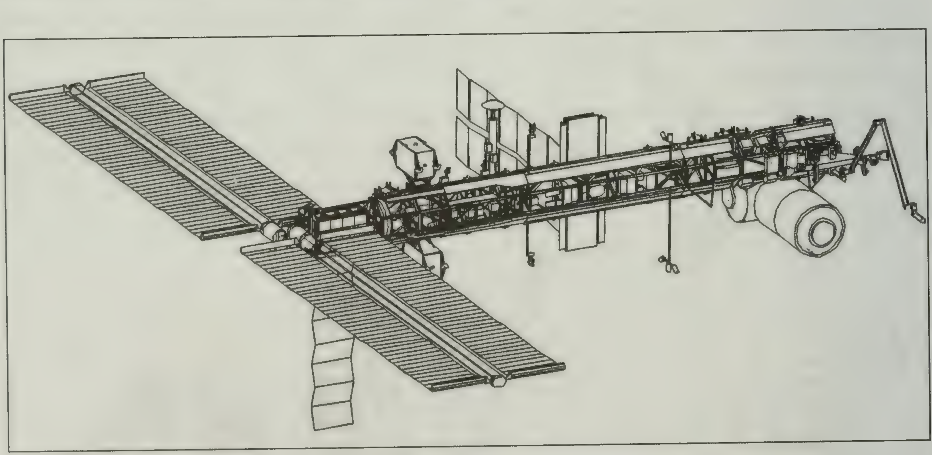

Figure 3–50. Man-Tended Capability, 1992.[117]

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[114] *National Aeronautics and Space Administration Authorization Act, Fiscal Year 1992*, Public Law 102-195, 102nd Congress, 1st sess. (December 9, 1991).

[115] *NASA Space Station Freedom Strategic Plan 1992*, undated. (NASA History Office Folder 16941).

[116] *Space Station Freedom User's Guide,* August 1992, pp. 2-1–2-2. (NASA History Office Folder 009554).

[117] *NASA Space Station Freedom Strategic Plan 1992*, p. 9.

The Station would orbit from 335 kilometers (208 nautical miles) to 460 kilometers (285 nautical miles) above Earth at a 28.5-degree inclination. An orbit around Earth would take approximately 90 minutes. Table 3–119 lists Space Station *Freedom* characteristics as of May 1992.

Russian Involvement

While NASA and Congress were embroiled in budget battles and restructuring of the Space Station, the leaders of the Soviet Union and United States were discussing cooperation in space. Early in July 1991, soon after dissolution of the Warsaw Pact, Vice President Dan Quayle and Oleg Shishkin, minister of General Machine Building in the Soviet Union, met to discuss a venture in which the United States and Soviet Union could cooperatively use *Mir* for human spaceflight missions.[118] On July 31, at a summit meeting in Moscow, President George H.W. Bush and Soviet President Mikhail Gorbachev signaled their growing cordiality by signing an agreement for an astronaut to visit *Mir* and a cosmonaut to fly on the Space Shuttle. The two also discussed Russia's desire to enter the commercial space launch market.[119] In December, Gorbachev resigned after an unsuccessful coup staged by hard-liners and the disintegration of the Soviet Union. Boris Yeltsin became the head of the new Russian Federation.

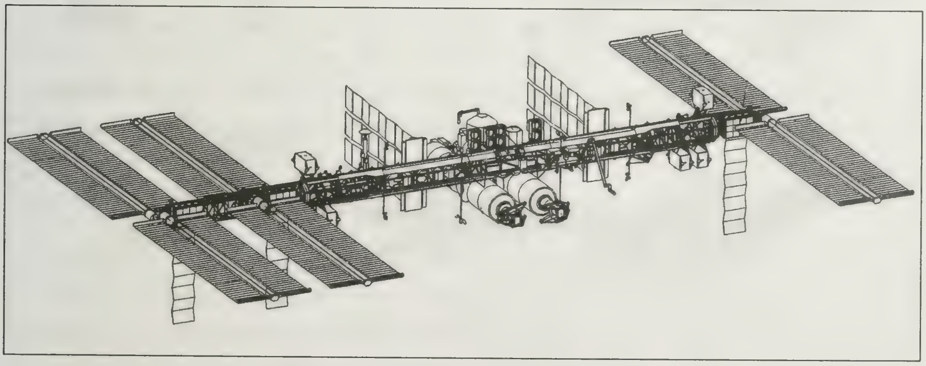

Figure 3–51. Permanently Manned Capability, 1992.

Soon after, in February 1992, President George H. W. Bush asked NASA Administrator Truly to resign. On April 1, Daniel Goldin assumed NASA's helm, inheriting a program that was behind schedule and over cost.[120] At roughly the same time, Yeltsin created the civilian Russian Space Agency headed by

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[118] Launius, p. 152.

[119] John M. Logsdon, "Appendix B: The Evolution of U.S.-Russian Cooperation in Human Space Flight," in John M. Logsdon and James R. Millar, eds., *U.S.-Russian Cooperation in Human Space Flight: Assessing the Impacts* (Washington, DC: Institute for European, Russian and Eurasian Studies, The George Washington University, 2001), *http://www.gwu.edu/~spi/usrusappb.html* (accessed June 3, 2005).

[120] W. Henry Lambright, *Transforming Government: Dan Goldin and the Remaking of NASA*, The PricewaterhouseCoopers Endowment for The Business of Government, March 2001, p. 19.

Yuri Koptev. The two new agency heads met informally in Washington, DC, to discuss possibilities for cooperation. This meeting was followed by a summit between President George H. W. Bush and Yeltsin on June 17, 1992, in which the two agreed "to give consideration to" a joint mission. The two leaders signed the "Agreement Between the United States of America and the Russian Federation Concerning Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes." The cooperation would include a "Space Shuttle and *Mir* Space Station mission involving U.S. astronauts and Russian cosmonauts." The leaders also agreed to a Shuttle flight by Russian cosmonauts in 1993, a flight on a long-duration mission on *Mir* by a U.S. astronaut in 1994, and a docking mission between the Shuttle and *Mir* in 1995.[121]

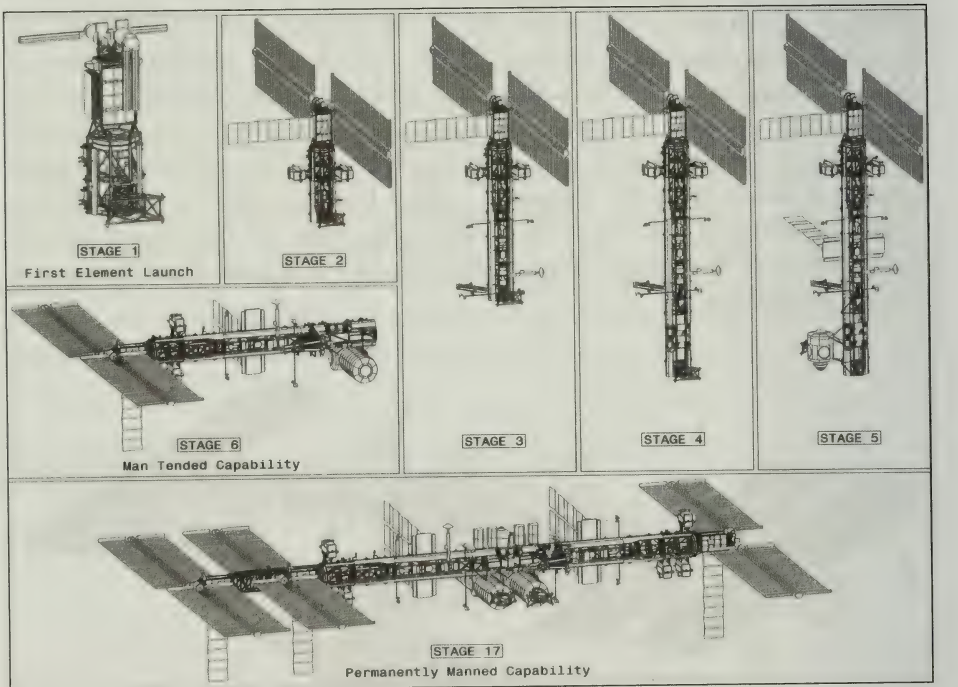

Figure 3–52. Space Station Freedom *Assembly Stages as Envisioned in July 1992, Showing the progression from Stage 1, First Element Launch, through Stage 6, Man-Tended Capability, to Stage 17, Permanently Manned Capability. (Grumman)*

On June 18, 1992, Russia and the United States formally signed a new U.S.-Russian Space Cooperation Agreement and ratified the first contract between NASA and the Russian aerospace firm NPO-Energia, a quasi-independent industrial conglomerate that ran the *Mir* space station. The agreement called for "a rendezvous [and] docking mission between the *Mir* and the Space Shuttle in 1994 or 1995"; "detailed technical studies of the possible use of [Russian] space technology" for U.S. missions, including Space Station *Freedom*; and "steps to encourage private companies to expand their search for new commercial space business."[122] The one-year contract with NPO-Energia, valued at $1 million, was to study applications of Russian space technology to the Space Station Freedom program. NASA also expressed interest in the potential use of the Soyuz as a crew rescue vehicle for Space Station *Freedom*, of Russia's automated rendezvous and docking system known as Androgynous Peripheral Docking Assembly being used with *Mir*, and of the *Mir* for long lead-time life sciences experiments in support of the Space Station Freedom program.[123]

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[121] "How 'Phase 1' Started," Shuttle-*Mir* Background, *http://spaceflight.nasa.gov/history/shuttle-mir/history/h-b-start.htm* (accessed June 3, 2005).

On October 5, 1992, NASA and the Russian Space Agency signed an "Implementing Agreement Between the National Aeronautics and Space Administration of the United States of America and the Russian Space Agency of the Russian Federation on HSF Cooperation." This agreement detailed the cooperation that had been called for in the June 1992 agreement and the necessary legal and other provisions associated with the cooperation. Particulars included an exchange of cosmonauts and astronauts on each other's spacecraft, with U.S. astronauts delivered to *Mir* by Soyuz, spending more than 90 days there, and returning on the Shuttle, Russian cosmonauts on *Mir* being "changed out" on the same Shuttle flight that would deliver a U.S. astronaut; and evaluation of the Russian Androgynous Peripheral Docking Assembly. The joint effort was named "the Shuttle-*Mir* Program."[124] The United States later proposed expanding the program to include more docking missions between the Shuttle and *Mir*, increasing the presence of U.S. astronauts on *Mir* to a maximum period of two years, and delivering up to two tons of hardware to the U.S. Space Station on Russian modules.

Redesign and Space Station Alpha[125]

In January 1993, William J. Clinton was inaugurated as President. One of his goals was reducing the federal deficit. A NASA assessment early in the year revealed that *Freedom* was $1 billion over budget.[126] The Office of Management and Budget warned Goldin that the President planned to cut NASA's budget and perhaps terminate Space Station *Freedom*. Goldin argued for the necessity of the Station to NASA's mission and existence.[127] President William J. Clinton reconsidered, and rather than cancel the program, directed NASA to redesign the Station and produce a configuration that reduced costs while still providing meaningful international participation as well as the "essential resources to advance the nation's scientific and technology development capabilities in space."[128] Consequently, on March 9, 1993, the President formally directed NASA to undertake a "rapid and far-reaching redesign of the Station" with a goal of significantly reducing development, operations, and utilization costs." The aim of this redesign was to cut the cost from the planned $14.4 billion to an administration goal of $9 billion and reduce the complexity of the current design and program while still achieving the goals for long-duration scientific research. The President directed NASA to give him several design options with various costs and capabilities.

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[122] Logsdon and Millar, Appendix B.

[123] "NASA Ratifies First Contract with Russian Space Program," *NASA News* Release 92-91, June 18, 1992, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1992/92-091.txt* (accessed June 3, 2005).

[124] Logsdon and Millar, Appendix B.

[125] Advisory Committee on the Redesign of the Space Station, "Final Report to the President," June 10, 1993, pp. 1–3, 21–24, 34, 40–41.

[126] Smith, *Space Stations*, 1999, p. CRS-3.

[127] Lambright, p. 17.

At the request of the U.S. Office of Science and Technology Policy, the Redesign Team was to consider options at three cumulative-cost levels: $5 billion, $7 billion, and President William J. Clinton's ceiling of $9 billion. The cost of each option for fiscal years 1994 through 1998 was to accommodate the international partners and cover total expenditures for the Station, including development, operations, utilization, Shuttle integration, facilities, research operations, and transition cost. The Station Redesign Team, led initially by Dr. Joseph Shea and subsequently by Col. Bryan O'Connor, first met on March 10, 1993. Over approximately three months, the Station Redesign Team developed three options.

An advisory committee, chaired by vice presidential appointee and MIT president, Dr. Charles Vest, beginning in April 1993, assessed each option, looking at technical and scientific capability, accuracy of projected costs, and structure of management and operations. The committee made a number of observations.[129] All three options had a firm requirement for an assured crew return capability—a space "lifeboat" or "parachute." The advisory committee noted that the United States was not currently developing such a vehicle, but that the Russian Soyuz spacecraft was considered a viable contender. The committee recommended changing the Station's inclination to 51.6 degrees to allow use of the Soyuz. White House guidelines included considering Russian participation and use of *Mir*, although later clarification from the White House emphasized that the redesign effort was not to focus on "present or future Russian capabilities."[130]

Redesign Options

Option A was a modular buildup using many *Freedom* systems. Option A eliminated the two U.S. nodes, simplifying the pressurized volumes. Many of the subsystems, including data management, software, electrical power, thermal systems, and pressurized modules, were also simplified. Option A contained two "sub-options," one with a Lockheed Bus-1 spacecraft for navigation and propulsion, the second without it. The Station would be 100 feet (30 meters) shorter than the original design. Permanent human capability would be achieved in September 2000 after 16 Shuttle flights. The total cost of Option A was $17 billion.

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[128] National Aeronautics and Space Administration, "Space Station Redesign Team Final Report to the Advisory Committee on the Redesign of the Space Station," June 1993, p. 259.

[129] The Advisory Committee was also called the Vest Panel.

[130] Logsdon and Millar, Appendix B.

Option B was derived most closely from Space Station *Freedom*. Except for minor changes, the phasing of capabilities and subsystems remained the same. Option B offered two advantages: 1) mature hardware, hardware mostly designed already with prototypes tested, and 2) the design of the baseline Station had evolved after years of engineering review and iteration with the research community. Option B used an evolutionary approach. The Option B Station was larger than the current design and would require 20 Shuttle flights to achieve an international permanent human capability in December 2001, and a greater number of EVAs. Option B's total cost was $19.7 billion.

Option C was a single-launch core Station and deviated most from the original design. All basic systems of this option would be checked out before launch, and it would be operational as soon the astronauts arrived. It had the largest inhabited volume and number of experiment racks. Because few of Option C's systems were mounted on the outside of the Station, less EVA maintenance was required, and therefore more crew time was available for research. This option placed a pressured module, derived from Space Shuttle components, in orbit with a single launch. Seven Shuttle flights would add international modules, and a permanent human capability would begin early in 2001. The total cost was $15.5 billion.

The advisory committee noted that none of the redesign options met the White House goal of completing development by the end of October 1998. The committee concluded, though, that Option A reached its human-tended configuration by that date. None of the options met the targets of $5 billion, $7 billion, or $9 billion. Even so, the proposed options, the committee believed, would still save from $6 billion to $10 billion when compared to the current anticipated cost of Space Station *Freedom* while permitting the development of a "very capable station."[131]

The advisory committee determined that Options A and C were "most deserving of further consideration." The international partners however, the report stated, expressed "strong reservations" about Option C based on this option's "relative lack of maturity and programmatic uncertainties." The committee also endorsed the Redesign Team's recommendation of a single prime contractor responsible for total system integration, including cost, schedule, and performance, and the establishment of a single NASA management team combining project and program levels into a dedicated program office and locating this core management team at a host Center.[132]

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[131] Advisory Committee on the Redesign of the Space Station, "Final Report to the President" (June 10, 1993), p. 40.

[132] Advisory Committee on the Redesign of the Space Station, "Final Report to the President" (June 10, 1993), pp. 1–3, 7, 34, 40.

On June 17, 1993, President William J. Clinton announced his selection of "a reduced cost, scaled-down version of the original Space Station *Freedom*." Called "*Alpha*," this was a hybrid of two options with a $10.5 billion price tag over FYs 1994–1998 and a total cost of $17.4 billion.[133] *Alpha* had four phases: "1) photovoltaic (PV) power station on-orbit for increased power to a docked orbiter/spacelab; 2) human tended capability (adding a U.S. Laboratory); 3) international human tended (adding an additional PV array and international modules); and 4) permanent human capability (adding a third PV array, the U.S. habitat module, and two Russian Soyuz capsules)."[134] The President also directed NASA to develop an implementation plan by September 1993 that included plans to continue and expand international participation to take advantage of political developments arising from the end of the Cold War.

The President's endorsement of the new Space Station failed to protect the project from attacks by Congress. In June, a vote to cancel the Station was defeated by only one vote. A week later, another bid to cancel the program failed by 24 votes. Furthermore, scientists continued to say that the new design had even fewer science benefits than before. With the end of the Cold War, the Station's political benefits had also evaporated.[135] Nevertheless, NASA moved ahead with the program. A Space Station Transition Team worked through July and August to refine Option A. On August 17, Goldin named Johnson Space Center as the host Center for the new Space Station program, reporting directly to NASA Headquarters, and Boeing Defense and Space Group as the prime contractor.[136] The change subordinated the other prime contractors, Grumman, McDonnell Douglas, and the Rocketdyne Division of Rockwell International, to Boeing and moved the program office from Reston, Virginia, to Houston, Texas, along with approximately 1,000 government and contractor jobs.

On September 7, President William J. Clinton formally chose the small, four-person *Alpha* Station approved in June. *Alpha* essentially merged the U.S. Space Station *Freedom* and the Russian *Mir-2* into a new Space Station, international in scope. Congress and the Administration agreed to a fixed annual budget of $2.1 billion and a total cap of $17.4 billion. This was below the required annual peak of $2.8 billion identified in the redesign. To manage with the allotted funds, NASA revised the assembly plans and slipped the scheduled permanent habitability capability date to September 2003.[137]

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[133] Lambright, p. 18. Also Smith, *Space Stations*, 1999, p. CRS- 3.

[134] Statement of the President, June 17, 1993 (NASA History Office Folder no. 009576). Also Launius, p. 178.

[135] Marcus Lindroos, "International Space Station (ISS) Plan," *Space Stations and Manned Spaceflight in the 1980s and 90s*, April 5, 2002, *http://www.abo.fi/~mlindroo/Station/Slides/sld061.htm* (accessed June 6, 2005).

[136] "Space Station Host Center and Prime Contractor Announced," *NASA News* Release 93–148, August 17, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-148.txt* (accessed May 23, 2005).

[137] Launius, p. 179.

Throughout the redesign process, President William J. Clinton worked to develop closer ties with the new Russian government. During April 3–4, 1993, President William J. Clinton and Vice President Albert A. Gore met with Russian leaders at a summit in Vancouver, Canada, with the goal of furthering cooperation in space. President William J. Clinton invited Russia to participate in the new Station, and Russian President Yeltsin agreed. This summit resulted in "a comprehensive strategy of cooperation to promote democracy, security, and peace" and establishment of the "United States-Russian Commission on technological cooperation in the areas of energy and space" working group headed by Albert A. Gore and Russian Prime Minister Viktor Chernomyrdin.

The United States-Russian Commission met on September 1–2, 1993.[138] One result from the meeting was agreement on a three-phase structure leading to a complete Space Station. The first phase, from 1994 to 1997, was the Shuttle-*Mir* program. It included up to 10 Shuttle flights to *Mir* as well as stays on *Mir* by U.S. astronauts. The second phase, from 1998 to 2000, would enable the Station to support three people. It included building the Station's core and an interface to the Shuttle and would involve the United States, Russia, and Canada. Russia would be paid $400 million as "compensation for services" during phases 1 and 2. The third phase, from 2000 to 2004, would complete the Station's assembly with European, Russian, and Japanese components in place.

On November 1, 1993, Goldin and Russian Space Agency Director Yuri Koptev signed an "Addendum to Program Implementation Plan" for Space Station *Alpha*. The plan described the overall concept of the relationship between NASA and the Russian Space Agency, the components and operations, and science and technology utilization during the three phases. It also laid out program management and financial management roles and responsibilities. It noted that "Russia will become a full international partner in the Space Station."[139] President William J. Clinton, however, was concerned about Russia's plan to sell missile technology to India. At a November 29 top-level White House meeting, an agreement was reached that Russia would be a new partner—"the primary partner," the Station would be designated the ISS, and Russia would cancel its planned sale of missile technology to India and receive $100 million annually from NASA to compensate for the canceled missile sale.[140]

For the most part, discussions between Russia and the United States had not involved the other Station partners, although they had been kept informed of progress, nor had they formally been asked to approve Russian participation in the program as a partner. On October 16, 1993, the United States met with its partners in Paris, France to formally inform them of its intent to invite Russia to join the Space Station program. On November 7, the partners jointly met with the Russian Space Agency to review the details of the November 1 addendum.

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[138] Logsdon and Millar, Appendix B.

[139] "Addendum to Program Implementation Plan," *Alpha* Station, November 1, 1993 (NASA History Office Folder 009576).

[140] Lambright, p. 18.

Finally, on December 6, 1993, in Washington, DC, the original Space Station partners decided to formally invite the Russian Federation to join the partnership. Over the next four years, the United States and partners worked to revise the Station intergovernmental agreements and memoranda of understanding to accommodate the Russian Federation. All the partners except Japan signed the new agreements on January 29, 1998.[141]

The Gore-Chernomyrdin Commission met again during December 16–17 in Moscow, Russia. There, Prime Minister Chernomyrdin announced that Russia had accepted the invitation to join the ISS program. Goldin and Koptev signed a protocol that expanded the terms of the 1992 HSF Cooperation agreement, detailing the activities that were to span the next decade and result in a completed Space Station. The two agencies agreed to up to 10 Shuttle flights to *Mir* with astronauts spending a total of 24 months on board the Station, a program of scientific and technological research, and the upgrade and extension of the *Mir* lifetime to the period 1995–1997. The protocol named some of the specific Shuttle missions for joint *Mir*-Shuttle activities.[142] Russia was to provide 12 hardware construction launches and six to eight utilization and resupply flights a year aboard Russian boosters.[143] Finally, Albert A. Gore and Chernomyrdin signed a "Joint Statement on Space Station Cooperation" describing the steps needed to formally bring Russia into the ISS partnership. It also noted that NASA and the Russian Space Agency had "agreed to contractual arrangements for up to $400 million through 1997 to facilitate the Shuttle-*Mir* program, joint technology developments, and the international Space Station."[144] This agreement ended a longstanding NASA practice that cooperative programs must not involve an exchange of funds.

The Shuttle-Mir Program

Russia has had more experience with long-duration spaceflight than any other nation, using the country's Soyuz spacecraft to ferry cosmonauts to and from Salyut space stations. The earliest Salyuts were equipped only for short stays, but beginning with its second-generation Salyut stations, the Soviet Union began sending crews into space for extended periods. Russia also used modified uncrewed Soyuz spacecraft, called Progress, to carry food, propellant, and supplies to these orbiting outposts.

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[141] John M. Logsdon, *Together in Orbit: The Origins of International Participation in the Space Station*, Monographs in Aerospace History, no. 11 (Washington, DC: National Aeronautics and Space Administration, 1988), pp. 42–43.

[142] "How Phase 1 Started," *http://spaceflight.nasa.gov/history/shuttle-mir/history/h-b-start.htm* (accessed July 14, 2006); Also "Protocol to the Implementing Agreement between the National Aeronautics and Space Administration of the United States of America and the Russian Space Agency of the Russian Federation on Human Spaceflight Cooperation," December 16, 1993. Cited and quoted in Launius, pp. 153–155.

[143] "Russia Joins Station Effort, Will Get $1 Billion Over Life of Project," *Aerospace Daily* (December 17, 1993): 441 (NASA History Office Folder 009576).

[144] "NASA and Russian Space Agency Sign Agreement for Additional Space Shuttle/*Mir* Missions," *NASA News* Release 93–222, 16 December 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-222.txt* (accessed June 6, 2005). Also "U.S.-Russian Joint Commission on Economic and Technological Cooperation: Joint Statement on Space Station Cooperation," December 16, 1993 (NASA History Office Folder 17040).

The final Salyut space station, *Salyut 7*, was abandoned in 1986 and reentered Earth's atmosphere over Argentina in 1991. The *Mir* space station replaced the Salyut. This third-generation space station was the world's first permanent space station, orbiting Earth since a Proton booster sent its core into space on February 20, 1986. The first *Mir* crew arrived in March 1986, and several Russian crews have spent extended periods on board *Mir*, sometimes for more than a year. Space travelers from other countries have also visited *Mir*.

Mir's modular design allowed several different vehicles or modules to be docked together (see Figure 3–53). Kvant-1 was added to the core module in 1987. This module housed the first set of six gyroscopes, instruments for astrophysical observations, and an experimental unit for electrophoresis. *Mir* also received an additional deployable solar panel.[145] Kvant-2, added in 1989, carried an EVA airlock, solar arrays, and life support equipment. Kristall, weighing 19.6 tons (17,781 kilograms), was added in 1990. This module carried scientific equipment, retractable solar arrays, and a docking node equipped with a special androgynous docking mechanism designed to receive spacecraft weighing up to 100 tons (90,718 kilograms).[146]

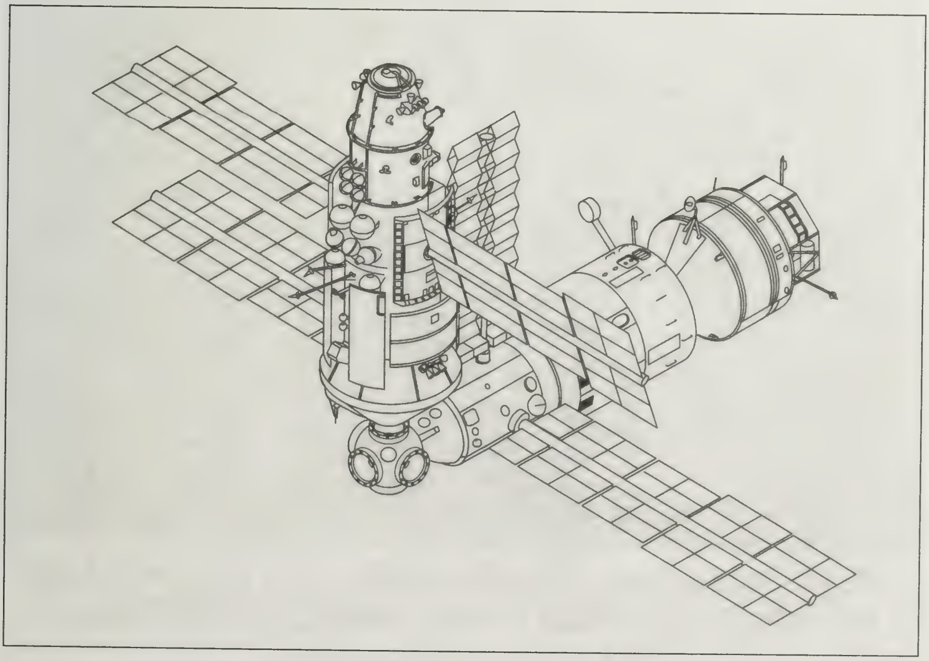

Figure 3–53. Mir *Space Station, 1989, with Base Block, Center; Kvant-1 Module, Right; and Kvant-2 Module, Top.*

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[145] "Kvant-1 Module," *http://www.russianspaceweb/com/Mir_kvant.html* (accessed June 8, 2005).

[146] Launius, p. 146.

The next *Mir* module to be installed, Spektr, was originally designed for military experiments but had been grounded for years after the intended launch date because of financial problems in the former Soviet Union. It was rescued in the mid-1990s with the advent of U.S.–Russian cooperation and was refurbished for its new role—to house experiments for the Shuttle-*Mir* program. Spektr was finally launched on a Russian Proton rocket on May 20, 1995, and was berthed at *Mir*'s radial port opposite Kvant-2 after Kristall was moved out of the way. The module carried four solar arrays and scientific equipment, including more than 1,600 pounds (726 kilograms) of U.S. equipment. Earth observation was the focus of scientific study for this module, specifically natural resources and atmosphere.

Piroda was the last science module added to *Mir*. It docked to *Mir* on April 26, 1996. Piroda's primary purpose was to add Earth remote sensing capability. Along with remote sensing equipment, Piroda carried hardware for materials processing and meteorological and ionospheric research and equipment for U.S., French, and German experiments.

The Shuttle-*Mir* program that would span three years was the first phase of the cooperative program leading to construction of the ISS. The program used the U.S. Space Shuttle and the Russian *Mir* to provide experience to American and Russian crews and to conduct early joint scientific research. The program objectives were to: 1) learn to work with an international partner; 2) reduce risks associated with developing and assembling a Space Station; 3) gain operational experience for NASA on long-duration missions; and 4) conduct life science, microgravity, and environmental research.[147] The program involved launching the Shuttle to take cargo to and from *Mir* and leaving U.S. astronauts aboard *Mir* for four to five months.

The program began February 3, 1994, on STS-63 when cosmonaut Sergei Krikalev became the first Russian to fly on a U.S. spacecraft to join his American colleagues on the Space Shuttle *Discovery*. The same mission demonstrated a close rendezvous between *Discovery* and *Mir*. The next year, on June 27, 1995, STS-71 collected Norman Thagard from *Mir*, who had spent 115 days on the Space Station after arriving aboard a Russian Soyuz TM-21 spacecraft. He was the first American to visit *Mir*. On this mission, the Space Shuttle *Atlantis* for the first time docked with *Mir* using the androgynous unit on the Kristall module that had been delivered to *Mir* in 1990. The photos below show a rendition of *Atlantis* docked to *Mir* (see Figure 3–54) and the two vehicles connected as photographed by a *Mir* crew member in the Soyuz (see Figure 3–55). Table 3–120 lists all Shuttle-*Mir* flights.

On STS-74 in November 1995, *Atlantis* delivered and permanently attached the new Androgynous Peripheral Docking Assembly to Kristall's androgynous docking unit. This docking module improved clearance between *Atlantis* and

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[147] Frank L. Culbertson, Jr., "Phase 1; Shuttle-Mir Program Overview," May 12, 1997 (NASA History Office Folder 15522). Also George C. Nield and Pavel Mikhailovich Vorobiev, ed., "Phase 1 Program Joint Report," NASA Special Publications 1000-6108/ (In English), National Aeronautics and Space Administration, January 1999, p. 3. (NASA History Office Folder 16480).

Mir's solar arrays on later docking flights. During the STS-74 flight, the Shuttle crew used the orbiter's remote manipulator system robot arm to hoist the docking module from the payload bay and berth its bottom androgynous unit atop *Atlantis*'s docking system. *Atlantis* then docked to Kristall. When *Atlantis* undocked from the docking module, the docking module remained permanently connected to Kristall.[148]

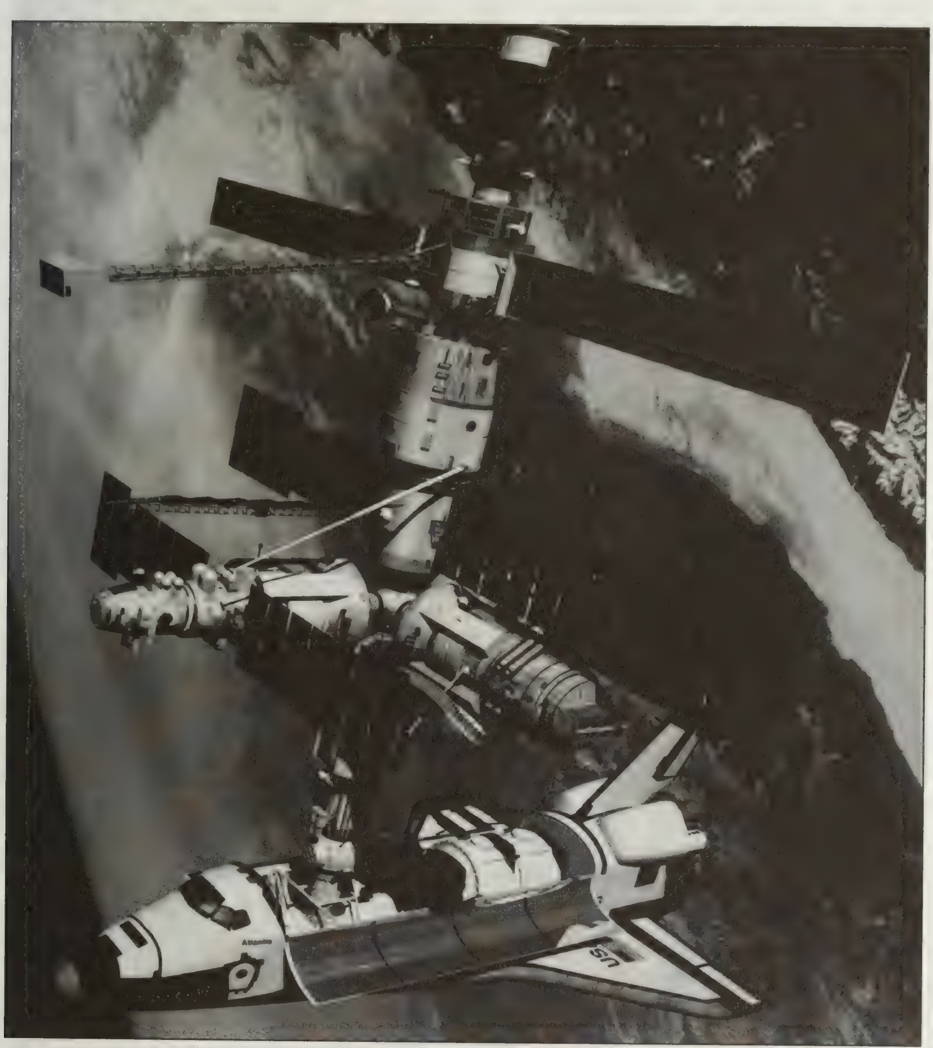

Figure 3–54. A technical rendition of the Space Shuttle Atlantis *docked to the Kristall Module of* Mir. *This configuration shows the STS-71/Mir Expedition 18 completed in June 1995. The Russian-developed Androgynous Peripheral Docking System linked the orbiter to the Kristall Module. (NASA Photo No. S-93-46073)*

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[148] "International Space Station: Russian Space Stations," NASA Facts, ISS-1997-06-004JSC, International Space Station, January 1997, *http://spaceflight.nasa.gov/history/shuttle-mir/references/documents/russian.pdf* (accessed June 7, 2005). Also "STS-74," *http://science.ksc.nasa.gov/shuttle/missions/sts-74/mission-sts-74.html* (accessed June 10, 2005).

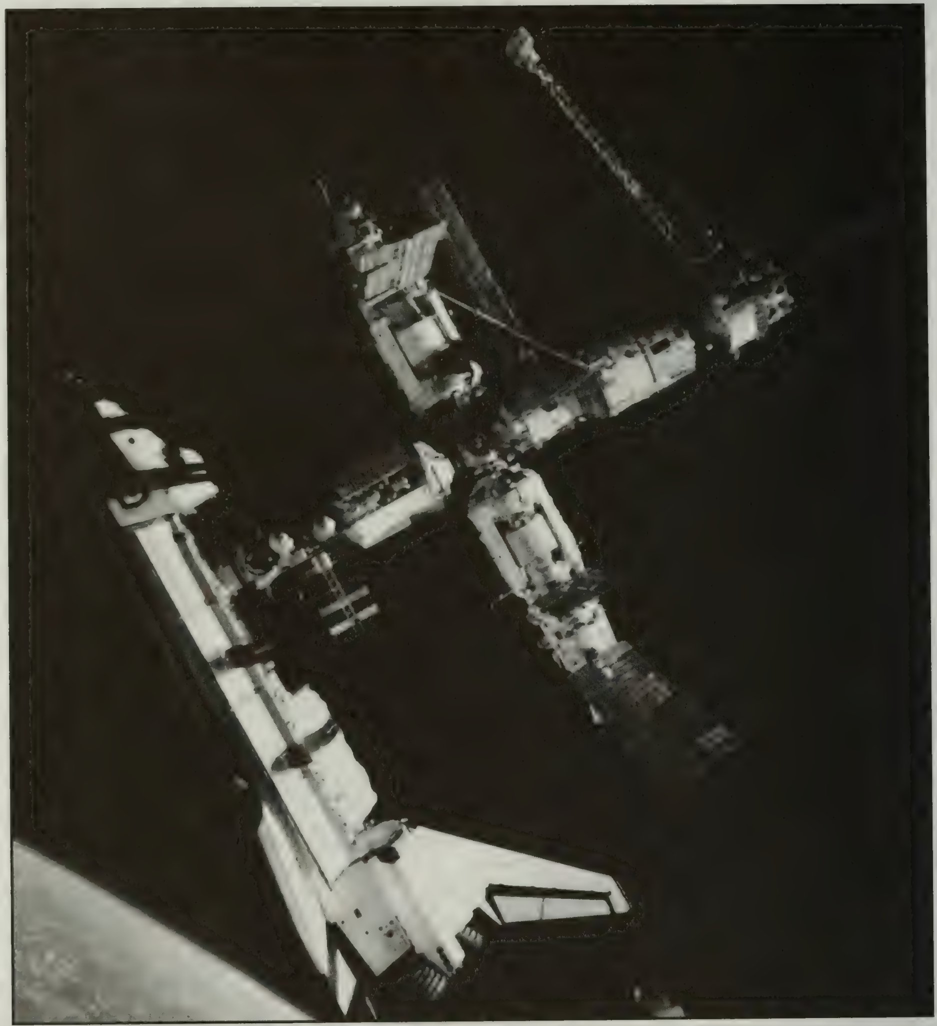

Figure 3–55. Undocking of Space Shuttle Atlantis *and* Mir *Space Station on STS-71. A* Mir *cosmonaut took this photo of* Atlantis *connected to Russia's* Mir *from a stationkeeping Soyuz on July 4, 1995. (NASA-MSFC Photo No. MSFC-9704176)*

A milestone occurred in 1997 when U.S. astronaut Jerry Linenger participated in the first U.S.-Russian EVA. On April 29, Linenger and *Mir* Commander Vasily Tsibliev conducted a 5-hour EVA to attach a monitor to the outside of the Station. The Optical Properties Monitor was to remain on *Mir* for nine months, studying the effects of the space environment on optical properties, such as mirrors used in telescopes.

In the midst of Shuttle flights to *Mir*, two serious accidents and a number of system problems on *Mir* raised doubts about the safety of *Mir* for U.S. crews and the reliability of the Russian equipment.[149] A fire on February 24, 1997, ignited in the Kvant-1 module when an oxygen canister malfunctioned. Of considerable size, the flames blocked access to one of the Soyuz spacecraft serving as a rescue vehicle. Although the fire burnt for only about 90 seconds, it filled the Station with sooty smoke, forcing the crew to wear masks and goggles until the area was cleared and it was certain there was no health hazard. It took a day of Station cleaning before the crew could return to their science mission.

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[149] Launius, p. 166.

In the months after the fire, the aging *Mir* experienced a number of systems failures and anomalies affecting such things as oxygen generation; carbon dioxide levels; temperature inside the habitable elements; crew exposure to ethylene glycol; power levels; power availability; air quality; and attitude control. The crew spent considerable time making repairs and keeping *Mir* habitable.

A life-threatening incident occurred on June 25, 1997, with astronaut J. Michael Foale aboard *Mir.* A Progress resupply vehicle loaded with garbage from *Mir* ran into the Spektr module while *Mir-23* Commander Vasily Tsibliev was attempting a test manual docking of the Progress using remote controls. The Progress flew off course, and the crew was unable to regain control of the tumbling cargo ship before it struck a solar panel on Spektr, destroying it. The Progress then bounced off the module, breaching the hull and buckling a radiator. Seconds later, a hissing sound alerted the crew to escaping oxygen, which was quickly traced to the Spektr module, now depressurizing, that the Progress had punctured. Crew members cut the cables leading into the Spektr, which sealed off the Spektr from the rest of the Station, and repressurized the remaining modules, leaving Foale's personal effects and several NASA science experiments inside the sealed-off area. For two days, the crew operated without power, which forced the shutdown of a number of key systems, including the oxygen generators and carbon dioxide scrubbers.

Meanwhile, the gyrodones which kept *Mir* in the proper attitude failed, destabilizing the vehicle and sending it into a spin that required firing the *Mir* engines to stop. Two weeks later, on July 7, another Progress vehicle brought supplies and repair materials to *Mir.* A fly-around of *Mir* and a 6-hour EVA on September 6, 1997 by Foale and *Mir* Commander Anatoly Solovyev to inspect damage to the Spektr module determined the location of the puncture on the module's hull.[150] The *Mir* crew pumped air into the module, and the Shuttle crew observed that the leak seemed to be located at the base of a damaged solar panel. The crew worked for months to return the damaged solar array to use, install a modified hatch so power lines could be routed while still keeping Spektr sealed, and restore damaged systems.[151] Because it was uncertain whether Spektr might again experience depressurization, even with repairs to the module, it remained sealed off and the scientific equipment in the module was lost.[152]

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[150] Launius, p. 169.

[151] Launius, pp. 167–169.

[152] Marcia S. Smith, "The Shuttle-Mir Program: Testimony Before the U.S. House of Representatives Committee on Science," September 18, 1997, *http://www.house.gov/science/smith_9_18.html* (accessed June 7, 2005).

The collision prompted Congress to call on NASA to conduct a safety review of *Mir* before allowing any more astronauts to visit the Station. Some, concerned with the safety of American crews and the advancing age of *Mir*, as well as Russia's ability to meet its obligations, demanded an end to the United States program with Russia. A Task Force Red Team, led by Maj. General Ralph Jacobson, conducted a safety assessment of *Mir* to decide whether to allow a long-duration stay of astronaut David Wolf on *Mir*. The Task Force recommended to Administrator Goldin that "it was safe to launch Dave Wolf to *Mir* on STS-86 and continue U.S. presence on *Mir* . . ."[153] It also reaffirmed the conclusions of NASA's internal reviews to proceed with plans to exchange U.S. astronauts on *Mir*. A. Thomas Young conducted an additional external assessment and endorsed the safety process.[154] Goldin decided to continue the program even though some members of Congress and the NASA Inspector General opposed it. The Shuttle-*Mir* program concluded with no further crises.

International Space Station

Background

The ISS evolved from the U.S. Space Station Freedom program and the Russian *Mir* space station program. Approximately 75 percent of the hardware created for *Freedom* provided by the United States and its international partners was incorporated into the ISS design, (see Table 3–121). When complete, the ISS will be the largest artificial structure ever to orbit Earth.

Development

Space Station *Freedom* was formally terminated on February 1, 1994, when NASA and contractor officials from Boeing, McDonnell Douglas, and the Rocketdyne Division of Rockwell International signed documents marking the end of the *Freedom* work package contracts. This consolidated responsibility for the design, development, and integration of the program under a single prime contract with Boeing Defense and Space Group. NASA and Boeing signed a major modification to the November 15, 1993, letter contract between the two parties, changing Boeing's scope of work from a transitional contract to a hardware design and development contract. Work on the components named in the work packages would continue with McDonnell Douglas and Rocketdyne as subcontractors to Boeing.[155]

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[153] Lt. Gen. Thomas P. Stafford, "Statement before the Committee on Science, U.S. House of Representatives, May 6, 1998," NASA Advisory Council Task Force on the Shuttle-*Mir* Rendezvous and Docking Missions and Task Force on International Space Station Operational Readiness, *http://www.house.gov/science/stafford_05-06.htm* (accessed June 8, 2005).

[154] "Panels Give Astronaut a 'Go' for Launch to *Mir*," *NASA News* Release 97-214, September 25, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-214.txt* (accessed June 8, 2005).

[155] "NASA Marks Space Station Milestone," *NASA News* Release 94-014, February 2, 1994, *http://www.nasa.gov/centers/johnson/news/releases/1993_1995/94-014.html* (accessed May 24, 2005).

There were frequent revisions to the ISS assembly schedule. In March 1994, the "preliminary" schedule in the November 1993 Implementation Plan was revised, and the first Shuttle launch was moved from July 1997 to December. The completion date slipped from October 2001 to June 2002. At the time, congressional critics expressed doubts about the cost and schedule savings that Russia's participation would provide and repeatedly introduced motions to cancel the program. The 103rd Congress, which met in 1993 and 1994, defeated five attempts to terminate the Space Station program in NASA funding bills and three other attempts in broader legislation.[156] NASA defended its actions by stating that the schedule slip resulted from the need to stay within the $2.1 billion annual budget ceiling. Table 3–122 lists the assembly schedule as of April 1994.

The most serious problems came from the financial and political circumstances of NASA's partners. The ESA stopped development of its Hermes spaceplane in 1993 and removed the attached pressurized module and free-flying platform from its list of contributions to the Station, leaving only its scaled down Columbus laboratory. Canada trimmed $400 million from its $1 billion contribution to the Station. Some of Russia's own launches were delayed because of lack of funds for rockets. Political unrest and instability in the splintered country resulted in dropped communication with *Mir* and damage to ground facilities. Although Russia's contributions were supposed to be "enhancing" rather than "enabling," the country's contributions were essential. The Station could not function without Russia's critical elements, which included the FGB, reboost and refueling, a service module, a power mast, and Soyuz spacecraft for emergency return. To counter charges that Russia would not carry out its commitments, NASA declared to Congress that, if given funds, it would buy, rather than lease, the FGB from its manufacturer, Khrunichev. Other backups were identified in case Russia did not meet its commitments.[157] The weak spot, NASA admitted, in the "critical path" was the service module, which the Russians were to develop as their principal contribution. NASA had no alternative to that element.

The ISS System Design Review, held in March 1994, was a major technical milestone. The Review confirmed the validity of the baseline configuration, schedule, and cost of the completed ISS. The ISS would operate at an altitude of approximately 240 nautical miles (444 kilometers) and would orbit at a 51.6-degree inclination (the *Mir* inclination) to offer better Earth observation opportunities. It would have six crew members and 33 standard user racks for science operations.

As summarized in the System Design Review, planned assembly was to begin with the launch of the Russian FGB in November 1997. A docking compartment would be added before the first U.S. launch in December 1997.

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[156] Smith, *Space Stations,* IB93017, 1996, *http://www.fas.org/spp/civil/crs/93-017.htm#legn* (accessed June 25, 2005).

[157] Bond, pp. 125–127.

The Russian service module was to be added to the Station in January 1998 followed by the universal docking module and the science power platform. The U.S. laboratory module would be launched on the third U.S. flight in May 1998. It would mark the beginning of human-tended science operations.

The Canadian-built robotic arm would be launched on the next flight in June 1998, and the addition of the Soyuz transfer vehicle in August 1998 would allow for extended on-orbit operations. The Japanese Experiment Module would be launched in early 2000, and the ESA laboratory module would be added in June 2001. Assembly would be complete in June 2002. The sequence provided for 13 Russian and 16 U.S. assembly flights. Use of the Ariane 5 launcher to lift the European module to the Station was added to the technical baseline. The U.S. contribution to the ISS, as stated in the System Design Review, was estimated at $17.4 billion from FY 1994 until assembly was complete in 2002.[158]

In April 1994, soon after the System Design Review ended, the heads of the various ISS agencies met in Washington to endorse the successful review and reaffirm their commitment to bringing Russia into the program as soon as possible.

Despite the successful review and the administration's support, criticism from Congress continued, and Congress introduced bills into the 1994 budget cycle to terminate the Station. But a bipartisan coalition of House legislators on June 29 defeated the motion 278-155. This vote was considered a signal that legislators felt that NASA was "getting its act together."[159] On August 3 the Senate rejected a similar motion to cancel the Station.[160]

In July 1994, the Space Station Control Board, which included representatives from NASA, the international partners, and Boeing, approved a revised assembly sequence (see Table 3–123). The new schedule substituted a U.S.-built solar array for a planned Russian-built array because of uncertainties whether the Russian array would be ready early enough in Station construction. This array fit between the Russian service module and the FGB. It would also provide more power to researchers during Phase 2. The U.S. truss would be attached temporarily to a small truss on top of the U.S. node and moved to a permanent position later in the assembly. The revised schedule moved launch of the third Station element, Russia's service module, from January to May 1998. The Board also agreed with U.S. plans to purchase the FGB from Khrunichev to assure its availability when ISS assembly began and the ESA plans to launch its laboratory module on an Ariane expendable launch vehicle rather than the Shuttle.[161]

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[158] "Space Station System Design Review Completed," *NASA News* Release 94-53, March 24, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-053.txt* (accessed June 8, 2005).

[159] "New Coalition of Lawmakers Gives Space Station Resounding Victory," *Aerospace Daily* 171, no. 1 (July 1, 1994): 1. (NASA History Office Folder 009577)

[160] "Goldin Hails Solid Senate Vote on Space Station," *NASA News* Release 94-127, August 3, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-127.txt* (accessed December 4, 2005).

[161] "Station Control Board Ratifies Improved Assembly Sequence," *NASA News* Release 94-117, July 15, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-117.txt* (accessed June 8, 2005). Also "Worries Over Russian Readiness Led to Station Schedule Shuffle," *Aerospace Daily* 171 (July 18, 1994): 87 (NASA History Office Folder 009577).

On August 31, 1994, NASA and Boeing agreed on key elements of the prime contract for the ISS. For the first time, NASA and Boeing concurred on the scope of work, program schedule, cost ceiling, and fee arrangement by fiscal year and on the completion and established contractual terms and conditions. NASA and Boeing hoped that the final contract would be in place before the end of the year.[162]

At the end of September, ISS managers released another updated assembly plan. This sequence incorporated early provisions for a centrifuge to augment the Station's science capabilities, allowed for earlier construction of Russia's Solar Power Platform in the late 1998 to mid-1999 timeframe, and meshed the latest weight estimates for Station components with Space Shuttle launch commitments. The change provided the Russian portion of the ISS with power and eliminated the need to transfer U.S. power to the Russian modules.[163]

The program to modify the Shuttle to increase lift capability, needed because of the launch to a higher inclination, was, according to a 1995 General Accounting Office (GAO) report, "challenging" and had a "questionable" schedule, "particularly in a declining budget environment." The assembly schedule continued to be complicated. It might be impossible, the GAO said, for the Shuttle to meet the demanding ISS assembly schedule. The GAO recommended that NASA obtain an independent review to assess the Agency's plans for increasing the Shuttle's lift capability, identify the associated risks, and weigh the costs and benefits of the tight scheduling of Shuttle flights for ISS assembly.[164] The program also had to overcome another attempt by the House of Representatives in a July 1995 vote to cut off funding for the program, ending ISS construction, and a similar Senate motion in September.[165]

ISS specifications and assembly schedules, as published by NASA, changed from 1994 through 1998. Updated assembly schedules were issued in September 1994, 1996, 1997, and 1998, each with later dates for assembling the various components.[166] Station mass also increased significantly from 831,000 pounds (376,935 kilograms) in 1994 to 924,000 pounds (419,119 kilograms) in 1996, and 1,015,000 pounds (460,396 kilograms) in 1998.[167]

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[162] NASA had selected Boeing as prime contractor in September 1993, and the two had signed a letter agreement in November. "NASA and Boeing Reach Agreement on Space Station Contract," *NASA News* Release 94-144, September 1, 1994, *ftp://ftp/hq.nasa.gov/pub/pao/pressrel/1994/94-144.txt* (accessed June 8, 2005).

[163] "Space Station Managers Release Updated Assembly Plan," *NASA News* Release 94-164, September 30, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-164.txt* (accessed December 2 , 2005).

[164] U.S. General Accounting Office, *Space Shuttle: Declining Budget and Tight Schedule Could Jeopardize Space Station Support* GAO/NSIAD-95-171, July 1995, pp. 1–2, 10, *http://www.gao.gov/archive/1995/ns95171.pdf* (accessed June 11, 2005).

[165] Patrice Hill, "House Democrats Fail in Effort To Kill Space Construction," *The Washington Times,* July 28, 1995. A6; "Senator Tries To Kill Space Station," *UPI*, September 26, 1995, *NASA Earlybird News*, NASA Public Affairs Office, News and Information Branch (NASA History Office Folder 16936).

[166] National Aeronautics and Space Administration "International Space Station (ISS) Phase I-III Overview," (undated, c. April 1995) (NASA History Office Folder 16936).

[167] "International Space Station: Assembly Complete With Shuttle," National Aeronautics and Space Administration Fact Sheet HqL-408, September 1994; "International Space Station: Assembly Complete," National Aeronautics and Administration Fact Sheet HqL-426, January 1996; "International Space Station Pocket Information Card," National Aeronautics and Space Administration, June 1998 (NASA History Office Folder 17083).

Construction

Construction of Space Station components and systems progressed while the Shuttle-*Mir* flights were occurring, although not without challenges and problems. The first major ISS event of 1995 occurred January 13, 1995, when NASA and Boeing signed a $5.63 billion contract to manage the building of the core Station, including two nodes, an airlock, and laboratory and habitation modules, as well as their integration. The contract also called for the design and development of the Station. With its other responsibilities, Boeing was directed to interact with NASA's international partners to ensure the compatibility of all the components. Soon after, NASA reached an agreement with the Russian Space Agency to purchase the FGB, the first ISS element. The two agencies signed a protocol on February 5 in Houston. Texas, reflecting the contract terms negotiated by Boeing subcontractor Lockheed Missiles & Space Co. and Khrunichev, the Russian manufacturer of the FGB. The agreement called for the design, development, manufacturing, test, and delivery of the FGB initially at a price of $190 million. By the time the contract was signed on August 15, the cost had risen to $210 million.[168]

In May 1995, the ISS completed a series of tests to evaluate elements of its Water Recovery System and its ability to remove bacteria, fungi, and live viruses from the water supply. It was the first time its ability to remove viral particles was assessed. Designers intended to recycle the Station's water supply once it was occupied. By mid-September, the United States had produced 54,000 pounds (24,494 kilograms) of ISS hardware, with nearly 80,000 pounds (36,287 kilograms) estimated to be produced by the end of the year. The international partners had manufactured a total of more than 60,000 pounds (27,216 kilograms). By the end of the summer, estimates predicted that Boeing alone would have built almost 41,000 pounds (18,597 kilograms) of ISS hardware, including pressurized aluminum modules where the Station crew would work, and the payload racks to house systems and experiments. Subcontractor McDonnell Douglas had delivered about 5,000 pounds (2,268 kilograms) of qualification and flight hardware. Rocketdyne had built about one-third of its hardware, including about 30 percent of the solar cells needed for the entire program—more than 75,000 solar cells according to Rocketdyne's program manager. Rocketdyne had also provided photovoltaic modules for a Russian-assembled replacement solar array that the Shuttle *Atlantis* would deliver to *Mir.* Astronauts were also well into their training for EVAs.

By the end of September, Boeing had successfully completed the main structure of the U.S. laboratory module. The structure consisted of three cylindrical sections, two bulkheads, and the hatch openings through which the astronauts would enter and exit. Also completed were critical design reviews on the communications and tracking systems, as well as demonstrations showing full compatibility between the ISS's S-band subsystem and NASA's TDRS System that the Shuttle used for communications and tracking.[169]

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[168] "NASA/Russian Space Agency Reach Agreement on Key Station Element," *NASA News* Release 95-13, February 8, 1995 (NASA History Office Folder 16936). Also Launius, pp. 181–182. "Boeing, Khrunichev Sign Contract for Space Station Element," *NASA News* Release 95-138, August 15, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-138.txt* (accessed June 8, 2005).

In January 1996, the exteriors of the U.S. Station modules were completed. One module was to house astronauts on board the ISS. Two nodes, a laboratory module and an airlock, were also completed. In May 1996, the air purification system passed a major test at Marshall Space Flight Center. The month-long test evaluated the air purification system's ability to control carbon dioxide, oxygen, and air pressure inside the living and laboratory quarters.[170] The next month, Rocketdyne successfully conducted tests in the neutral buoyancy simulator on a mockup of a truss that would house the communications and tracking, attitude stabilization, thermal control, and electrical power distribution systems.[171] In November, the first U.S. module, Node 1, successfully completed its final pressure test at the Boeing plant in Huntsville, Alabama. Node 1 was shipped to Kennedy Space Center in June 1997.

International Contributions

Although the ESA was scheduled to contribute the Columbus laboratory module, by mid-June 1995 the ESA still had not reached agreement over the size and scope of its involvement in the Space Station.[172] On October 18, the ESA Council met in Toulouse, France, and approved the program "European Participation in the International Space Station Alpha." The program incorporated a number of cutbacks from earlier plans because of financial constraints. The approved program consisted of the following:

- Columbus laboratory development and launch, a module permanently attached to the ISS for conducting scientific experiments, research, and development.
- The Automated Transfer Vehicle (ATV), a logistics vehicle launched by an Ariane 5 for carrying research and system equipment, gases, and propellant to the ISS, and removing trash from the Station.
- Station utilization preparation and astronaut-related activities.

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[169] "Space Station Completes Major Life Support System Tests," *NASA News* Release 95-61, May 3, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-61.txt* (accessed June 8, 2005); Frank Morring, Jr., "Space Station: Contractors Say Project Well Underway; Schedule Critical," *Focus, a Supplement to Aerospace Daily* (May 19, 1995): p. 278 (NASA History Office Folder 16936); "U.S. Structure for International Space Station Completed," *NASA News* Release 95-161, September 26, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-161.txt* (accessed June 8, 2005); Dave Cooling, "Research Outpost Beyond the Sky," *IEEE Spectrum* (October 1995):.28-33 (NASA History Office Folder 16936).

[170] "Space Station Air Purification System Completes Major Test," *NASA News*, Marshall Space Flight Center Release 96-96, May 10, 1996, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1996/96-96.txt* (accessed June 14, 2005).

[171] "Space Station Truss Tested in Neutral Buoyancy Simulator," *NASA News*, Marshall Space Flight Center Release 96-121, June 13, 1996, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1996/96-121.txt* (accessed June 14, 2005).

[172] Peter B. deSelding, "ESA's Role in Space Station Still Shaky," *SpaceNews* 6 (June 19–25, 1995): p. 1 (NASA History Office Folder 16936).

- Studies of a European Crew Transport Vehicle (CTV), leading to involvement in the X-38 demonstrator and possible participation in the Crew Return Vehicle.
- Exploitation of the results of the Atmospheric Reentry Demonstration (developed under the Hermes program) for the ATV and CTV.

Soon after the Toulouse conference, the ESA and its prime contractor, Daimler Benz Aerospace, signed a contract to undertake Columbus laboratory development using a consortium of European subcontractors.[173] Table 3–124 lists the Columbus laboratory characteristics.

The ESA intended to use an Ariane 5 to launch Columbus. But on June 4, 1996, the first Ariane 5 launch failed, destroying the launch vehicle and its payload. The ESA decided against using the Ariane to launch Columbus, and NASA agreed to launch Columbus on the Shuttle. In return, Alenia Aerospazio, an Italian space company under contract to the Italian Space Agency, would supply the second and third nodes of the ISS, saving NASA the cost of building them.[174] The Italian Space Agency also agreed to provide three pressurized Multi-Purpose Logistics Modules. With the ability to be attached to both the Station and the Shuttle and with components to provide some life support, the modules would serve both as "moving vans" by carrying equipment, experiments, and supplies between the ISS and the Shuttle, and as attached Station modules. While traveling between the ISS and Earth, these modules would be isolated, and crew members could not enter them from the Shuttle cabin. This would retain the Station environment.

Construction of the first Italian module, named Leonardo, began in April 1996 at the Alenia Aerospazio factory in Turin, Italy. A special Beluga cargo aircraft delivered the module to Kennedy Space Center from Italy in August 1998, with launch planned for 2001. The cylindrical module was approximately 21 feet (6.4 meters) long and 15 feet (4.6 meters) in diameter. The module weighed almost 4.5 tons (4,082 kilograms) and could carry up to 10 tons (371,946 kilograms) of cargo packed into 16 equipment racks. Two more multipurpose modules, named Raffaello and Donnatello, were planned for later Shuttle flights.[175] Figure 3–56 shows Leonardo being processed at Kennedy Space Center.

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[173] European Space Agency, *Columbus: Europe's Laboratory on the International Space Station*, BR-144, October 1999, pp. 5–7.

[174] Harland and Catchpole, pp. 190–91, 196. Also "Space Station Assembly Elements: U.S. Node 2," http://spaceflight.nasa.gov/station/assembly/elements/node2/index.html (accessed June 15, 2005).

[175] "Space Station Assembly: Multi-Purpose Logistics Modules," *http://www.nasa.gov/mission_pages/station/structure/elements/mplm.html* (accessed June 20, 2005); "Leonardo Module: A 'Moving Van' for the International Space Station," *NASA Facts*, Johnson Space Center, IS-1998-10-ISS021-JSC, November 1998, *http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/mplm.pdf* (accessed June 15, 2005).

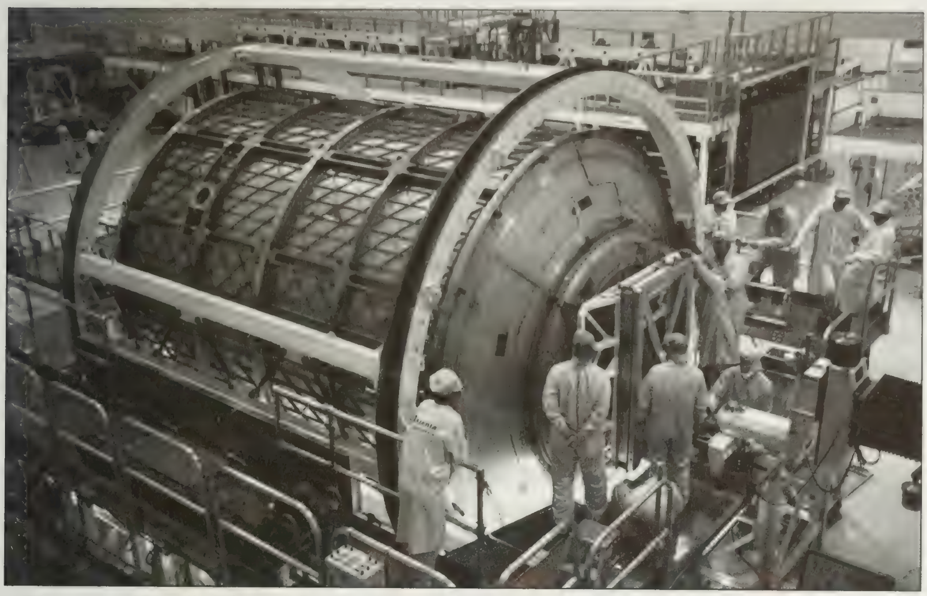

Figure 3–56. Processing of Leonardo, the first multi-purpose logistics module, takes place at Kennedy Space Center on December 3, 1998. The module was one of three from Italy's Alenia Aerospazio. Leonardo will be operated by NASA and supported by the Italian Space Agency. (NASA-KSC Photo No. KSC-98PC-0892)

On October 14, 1997, NASA and the Brazilian Space Agency (AEB), a new international partner, signed an implementing arrangement providing for the design, development, operation, and use of Brazilian-developed flight equipment and payloads for the ISS. In exchange for AEB-supplied equipment and support, NASA would give Brazil access to NASA ISS facilities on orbit and a flight opportunity for one Brazilian astronaut.[176]

Problems with Russia

Although construction was progressing on the Russian FGB, and the module would be assembled and ready for testing in December 1996, Russia's persistent lack of funds was causing a major program crisis.[177] In December 1995, the Russian Space Agency announced that the Russian government owed FGB manufacturer Khrunichev money for 1995 work and, unless the Russian government released the funds needed to work on the FGB and the service module, it would be unable to meet the FGB's launch date and unable to build the service module, both essential components. On March 27, 1996, NASA Administrator Goldin stated that he would give Russia one month or six weeks to get "stalled . . . effort moving again." But by July, Khrunichev had received only a letter as a guarantee in seeking a loan to fund work on the service module, which was now acknowledged to be "months" behind schedule. By late September, it seemed unlikely that the service module would be ready to launch in April 1998. At the end of 1996, the Russian Space Agency acknowledged that the service module would have to be delayed still further to December 1998 because the promised funds had not arrived.[178]

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[176] "NASA Signs International Space Station Agreement with Brazil," *NASA News* Release 97-233, October 14, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-233.txt* (accessed June 14, 2005).

[177] "Station's First Module Assembled; Ready for Testing," *NASA News* Release 96-253, December 9, 1996 (NASA History Office Folder 17083).

In the meantime, early in 1997, NASA allocated $100 million to Lockheed to initiate development of the Interim Control Module as a backup, based on the propulsion module of a classified military satellite. The Interim Control Module could provide propulsion until the service module became available, although the interim module would require substantial modifications and would cost time and money. At this point, Russia was seriously in danger of being dropped from the program. Although promises were forthcoming, money was not. In April, NASA and the Russian Space Agency formally agreed to slip launch of the FGB from November 1997 to mid-1998, 11 months later than originally planned, and to launch the Interim Control Module if the service module could not be launched later in 1998. NASA also stated that it would devote "equal attention" to contingency planning. On April 9, 1997, NASA announced that the ISS's on-orbit assembly was slipped to "no later than" October 1998.[179] On April 11, the Russian government arranged for bank loans to Energia by the end of May. Khrunichev soon resumed work on the service module, and NASA expressed "cautious optimism" that the ISS was back on track.

Cost and Schedule Problems

On May 15, 1997, the Space Station Control Board released a new assembly schedule, Revision C.[180] According to this revision, the FGB would launch in June 1998, eight months later than earlier planned; the U.S. node would launch in July; and the service module would launch in December (see Table 3–125). A Shuttle flight was added as a contingency to send up the Interim Control Module in December 1998 if delivery of the service module slipped into 1999.[181] On May 31 at a meeting in Tokyo, the heads of the five participating space agencies accepted the revised schedule. NASA also requested that Congress create a new Russian Program Assurance budget category to finance construction of the Interim Control Module and other contingency options.

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[178] Harland and Catchpole, pp. 191–194.

[179] "NASA Revises International Space Station Schedule," *NASA News* Release 97-65, April 9, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-065.txt* (accessed June 13, 2005).

[180] "Assembly Sequence, 5/15/97 Rev C," National Aeronautics and Space Administration, International Space Station (NASA History Office Folder 11613); "Space Station Control Board Approves New Assembly Schedule," *NASA News* Release 97-98, May 15, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-098.txt* (accessed June 13, 2005).

[181] Harland and Catchpole, pp. 191–197.

A September 1997 meeting in Houston, Texas, of representatives of all the ISS partners formally approved Revision C of the assembly and launch schedule that had received preliminary approval in May. The first U.S.-built Station element, Node 1, was scheduled to launch on STS-88, the first Shuttle assembly mission, in July 1998. In June 1997, Node 1 had been shipped from Alabama to Kennedy Space Center to begin launch preparations. The schedule called for launch of the ESA's Columbus in October 2002. The Russian service module was scheduled for a December 1998 launch. At an earlier General Designer's Review, the Russian Space Agency had assured NASA that it could meet the scheduled launch date. The first ISS element, the Functional Cargo Block, was "on track" for a June 1998 launch. The module had completed manufacturing at Khrunichev on September 15 and had been moved to the RSC-Energia facilities for further testing.[182] However, in November it was announced that, because of manufacturing problems, the module had fallen two months further behind schedule and the time was unlikely to be recovered.[183]

Cost continued to be a problem. From 1996 to 1997, cost overruns on the project increased at an alarming pace. In 1997, the GAO released two reports before the Senate Subcommittee on Science, Technology, and Space reporting on the program's cost and schedule status and estimated cost at completion. The June report stated that Russia's inability to meet its financial responsibilities had resulted in a projected eight-month delay in launching the service module. The GAO report also said that cost control problems under the prime contract had "steadily worsened." Since April 1996, the cost overrun "more than tripled" to $291 million.[184] On September 18, 1997, the GAO released a second report updating the status of the ISS prime contractor's cost and schedule performance. The situation, the GAO now claimed, had continued to worsen from a cost overrun of $291 million in April 1997 to a cost overrun of $355 million as of July 1997.[185] In September 1997, NASA and Boeing revealed that Boeing's prime contract would have at least a $600 million overrun at completion, and NASA needed $430 million more than expected in FY 1998.[186] In November, prime contractor Boeing admitted to a House panel that Boeing's costs were millions of dollars over the company's contract amount.

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[182] "Control Board Reports International Space Station Launch on Target, Finalizes Assembly Sequence," *NASA News* Release 97-222, October 1, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-222.txt* (accessed June 14, 2005).

[183] "NASA Says Russian Service Module Two Months Behind Schedule," *Aerospace Daily* 184 (November 6, 1997): p. 201 (NASA History Office Folder 16949).

[184] U.S. General Accounting Office, "Space Station: Cost Control Problems Continue To Worsen," Testimony Before the Senate Subcommittee on Science, Technology, and Space, June 18, 1997, *http://www.gao.gov/archive/1997/ns97177t.pdf* (accessed June 15, 2005).

[185] U.S. General Accounting Office, "Space Station: Deteriorating Cost and Schedule Performance under the Prime Contract," Testimony of Allen Li Before the Senate Subcommittee on Science, Technology, and Space, GAO/T-NSIAD-97-262, September 18, 1997, p. 1, *http://www.gao.gov/archive/1997/ns97262t.pdf* (accessed June 15, 2005).

[186] Smith, *Space Stations*, IB93017, May 16, 2001, CRS Issue Brief for Congress, *http://www.ncseonline.org/NLE/CRSreports/Science/st-58.cfm* (accessed March 2, 2005). Also Catchpole, pp. 197–198.

In September 1997, Administrator Goldin requested that the NASA Advisory Council establish a "cost control task force . . . on the International Space Station . . . to conduct a prompt, independent, and thorough analysis" of the . . . "factors that affect cost growth and control . . . " The task force, chaired by Jay Chabrow, delivered its report to the Advisory Council on April 15, 1998. Although the report credited the program with having made "notable and reasonable progress," the report estimated that NASA would need an extra $7 billion, increasing the 1993 estimate of $17.4 billion to $24.8 billion, and up to three more years to complete the project. The report attributed the cost overrun to "program size, complexity, and ambitious schedule goals . . . beyond that which could be reasonably achieved within . . . the $17.4 billion total cap."[187] Russian participation also was a "major threat" to the program. Rather than the anticipated $1 billion cost savings to the United States from Russia's provision of the FGB and an Assured Crew Return Vehicle, Russia's economic situation had negated most of the savings, depleted a major part of program reserves, and caused schedule slips.[188]

In NASA's response to the Task Force report released on June 15, 1998, NASA identified approximately $1.4 billion in additional costs. The response also noted that after the report's release, the assembly schedule was changed once more to accommodate a four-month service module schedule slip (Revision D). Consequently, the first-element launch (the FGB) was moved to November 1998 with ISS assembly complete by January 2004.[189] On May 31, representatives of all ISS partners agreed to officially target a November 1998 launch for the first ISS component and to revise launch target dates for the remainder of the assembly plan. The partners set an April 1999 target launch date for the service module, and the first ISS crew would be launched aboard a Soyuz spacecraft in the summer of 1999 to begin a five-month stay on the Station.[190] Table 3–126 shows a partial assembly sequence as of May 1998.

January 29, 1998, marked an important ISS milestone. On that day, senior government officials from 15 countries met in Washington, DC, and signed agreements establishing the framework for cooperation among the partners for the design, development, operation, and utilization of the ISS. The "Space Station Intergovernmental Agreement," signed by Canada, 11 member states of the ESA, the Russian Federation, Japan, and the United States, established "a long term international cooperative framework on the basis of genuine partnership . . . of a permanently inhabited civil Space Station for peaceful purposes, in accordance with international law." (See Figure 3–57 for the commemorative plaque issued in honor of the signing.) NASA Administrator Goldin also signed three bilateral memoranda of understanding (MOU) with the heads of the Russian Space Agency, ESA, and the Canadian Space Agency on January 29, and with the government of Japan on February 24. These MOUs described in detail the roles and responsibilities of the agencies in the design, development, operation, and utilization of the ISS. They spelled out the management structure and interfaces necessary to ensure the effective operation and utilization of the ISS. These new agreements superseded previous ISS agreements signed in 1988 among the United States, Europe, Japan, and Canada, reflecting changes to the program resulting from Russian participation in the program and the 1993 design changes.[191]

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[187] NASA Advisory Council, "Report of the Cost Assessment and Validation Task Force on the International Space Station," Apri 21, 1998, *http://history.nasa.gov/32999.pdf* (accessed June 12, 2005).

[188] "Report of the Cost Assessment and Validation Task Force on the International Space Station," April 21, 1998. *http://history.nasa.gov/32999.pdf* (accessed July 18, 2006).

[189] "International Space Station (ISS) Response to the Cost Assessment and Validation Task Force on the ISS," June 15, 1998, *http://spaceflight.nasa.gov/spacenews/releases/1998/cav_response.pdf* (accessed June 15, 2005).

[190] "International Space Station Partners Adjust Target Dates for First Launches, Revise Other Station Assembly Launches," *NASA News* Release 98-93, June 1, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-093.txt* (accessed June 21, 2005).

On-Orbit Assembly Begins

On-orbit assembly of the ISS began November 20 with the launch of Russia's Functional Cargo Block (renamed Zarya, meaning "sunrise") to orbit by a Russian Proton rocket from the Baikonur Cosmodrome in Kazakhstan. Work on this U.S.-funded module had begun in 1994 and was completed in 1998.[192] Zarya provided the ISS's initial propulsion and power. Characteristics of Zarya are listed in Table 3–127.

The first U.S. component of the ISS, Node 1, was launched on December 3, 1998, on mission STS-88 (see Figure 3–58 for the module inside the *Endeavour*'s payload bay). The module was named "Unity" to commemorate the joining of ISS modules from Russia and the United States and to honor the spirit of international cooperation and achievement in building the Station. Unity provided six docking ports for the attachment of other modules. Unity also provided external attachment points for the truss and internal storage and pressurized access between modules. Two PMAs connected Unity to *Endeavour* at one end and to Zarya at the other. The PMAs also provided passageways for crew, equipment, and supplies. PMA-1 connected to Zarya using an Androgynous Peripheral Attach System similar to the Russian docking system used for Shuttle-*Mir* docking. The other end of the PMA connected to Unity using a Passive Common Berthing Mechanism. PMA-2 linked the Shuttle to Unity using an Androgynous Peripheral Attach System provided with a hatch that had an 8-inch (20-centimeter) viewport. The other end attached to Unity using a Passive Common Berthing Mechanism. Figure 3–59 shows interior and exterior views of Unity. Table 3–128 lists Unity's characteristics.

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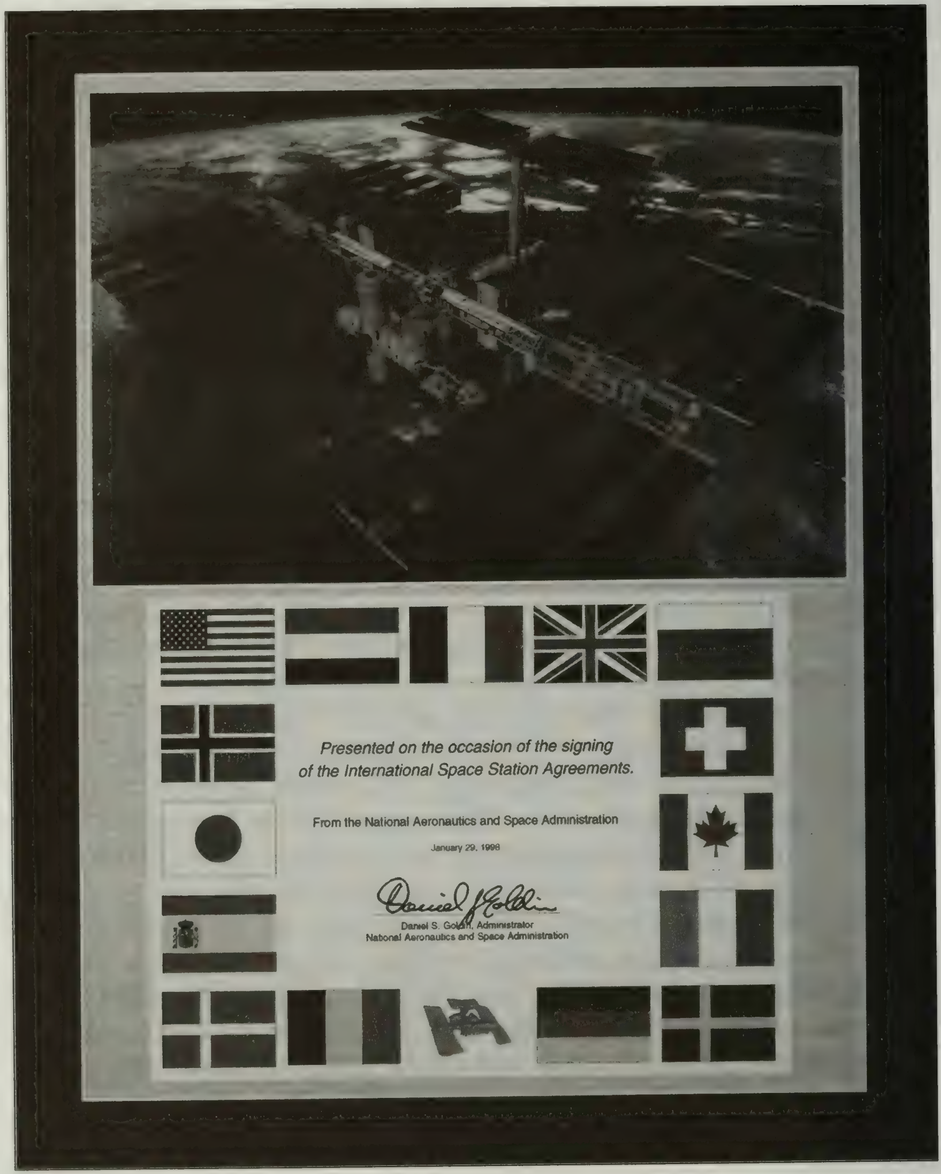
[191] "Partners Sign ISS Agreements," National Aeronautics and Space Administration, *http://spaceflight1.nasa.gov/station/reference/partners/special/iss_aggrements/* (accessed June 21, 2005). Also "Space Station Agreements," ESA, *http://www.spaceflight.esa.int/users/file.cfm?filename=fac-iss-la-ssa* (accessed June 21, 2005).

[192] The module was built by the Khrunichev State Research and Production Space Center in Moscow under a subcontract to The Boeing Company for NASA. "Space Station Assembly Elements: Zarya Control Module,"*http://spaceflight.nasa.gov/station/assembly/elements/fgb/index.html* (accessed December 3. 2005).



Presented on the occasion of the signing of the International Space Station Agreements.

From the National Aeronautics and Space Administration

January 29, 1998

Daniel S. Goldin, Administrator
National Aeronautics and Space Administration

*Figure 3–57. This commemorative plaque was presented on the signing of the International Space Station Agreements (*http://spaceflight.nasa.gov/station/reference/partners/special/iss_aggrements/ISS_Agreements_lo.jpg*).*

On December 5, the 12.8-ton (11,612-kilogram) Unity connecting module was first attached to *Endeavour*'s docking system. On December 6, using the Shuttle's 50-foot (15.2-meter) robot arm, Zarya was captured from orbit, and the two units docked. Figure 3–60 shows the Canadian-built remote manipulator system maneuvering astronauts Newman and Ross into position to work on the Unity module. Figure 3–61 shows the two modules docked together.

On December 7, 9, and 12, astronauts Ross and Newman conducted three spacewalks to:

- Attach PMA-1 to Zarya.
- Test a SAFER unit, a self-rescue device should a spacewalker become separated from the spacecraft during an EVA.
- Nudge two undeployed antennas on Zarya into position.
- Remove launch restraint pins on Unity's four hatchways for mating future ISS modules and truss structures.
- Install a sunshade over Unity's two data relay boxes to protect them against harsh sunlight.
- Stow a tool bag on Unity.
- Disconnect umbilicals used for the mating procedure with Zarya.
- Install a handrail on Zarya.
- Make a detailed photographic survey of the Station.

The astronauts completed assembly of an early S-band communications system allowing flight controllers in Houston, Texas, to send commands to Unity's systems and monitor the Space Station's health. The astronauts also conducted a successful test of the videoconferencing capability of the early communications system that the first permanent crew would use. Mission Specialists Krikalev from Russia and Currie also replaced a faulty unit in Zarya.

Unity and Zarya were successfully engaged at 9:48 p.m. on December 6, and Unity came to life at 10:49 p.m. on December 7. At 2:54 p.m. on December 10, history was made as Shuttle Commander Cabana and Krikalev floated into the ISS together, followed by the rest of the crew. At 4:12 p.m., Cabana and Krikalev opened the hatch to Zarya and entered. On December 11, at 5:41 p.m., Cabana and Krikalev closed the hatch to Zarya, and they closed the door to Unity at 7:26 p.m. The ISS flew free at 3:25 p.m. on December 13, as Shuttle Pilot Sturckow separated *Endeavour* from the ISS. Orbital events relating to the Zarya and Unity missions are listed in Table 3–129.

Laboratory Accommodations

The laboratories provided by the United States and the international partners were to focus on six major research disciplines: microgravity science, life science, space science, Earth science, engineering research and technology, and space product development. Table 3–130 provides an overview of the ISS science laboratories as of early 1999.

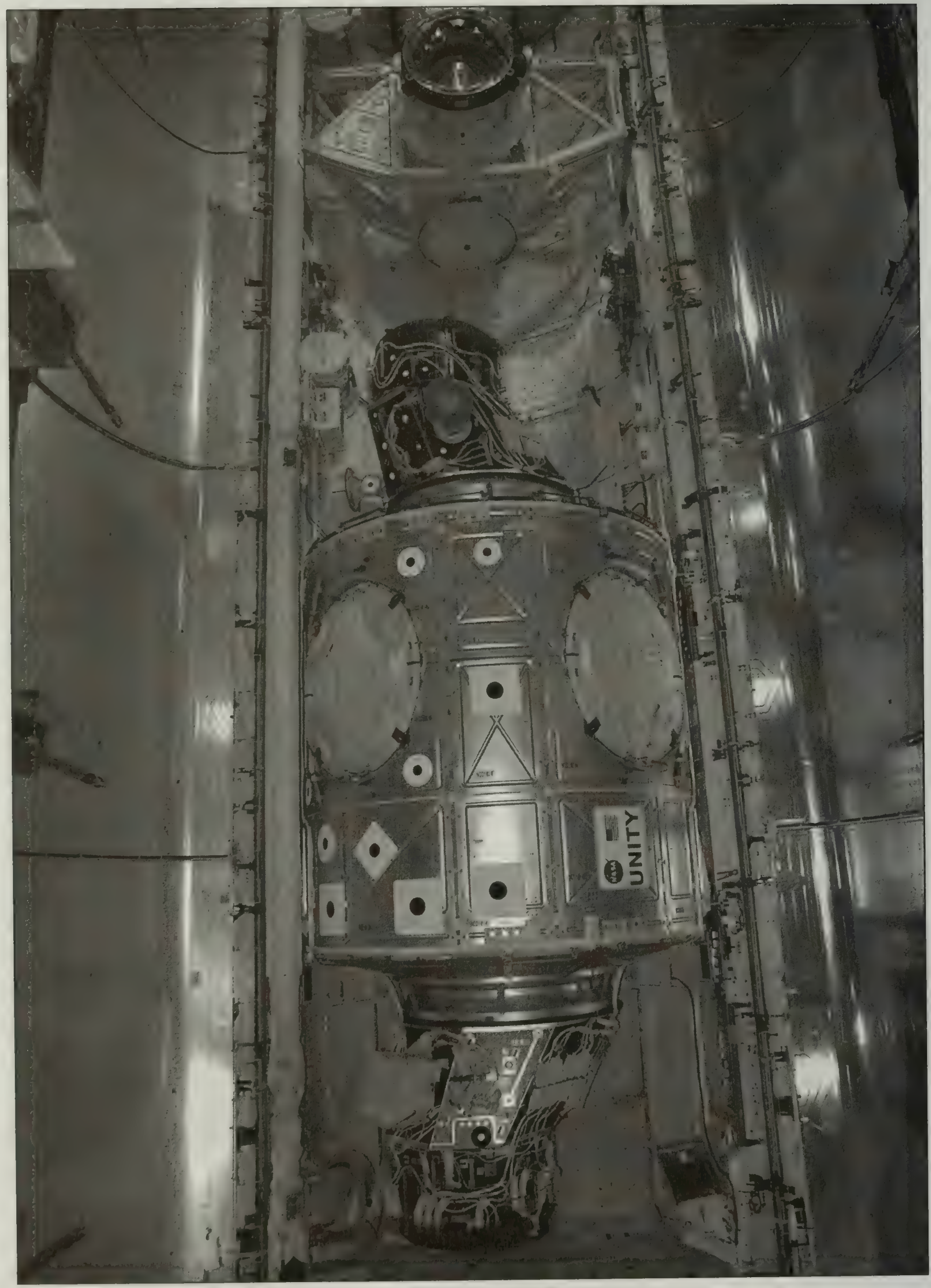


Figure 3–58. The Unity Module Inside the Payload Bay of Space Shuttle Endeavour, *November 19, 1998.*

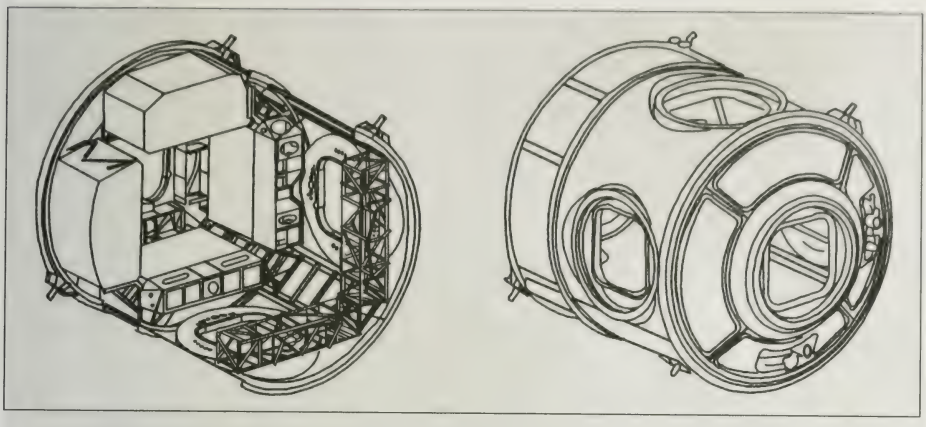


Figure 3–59. Diagram of Interior and Exterior of Unity Connecting Module. (NASA Photo No. 98PC-1731)

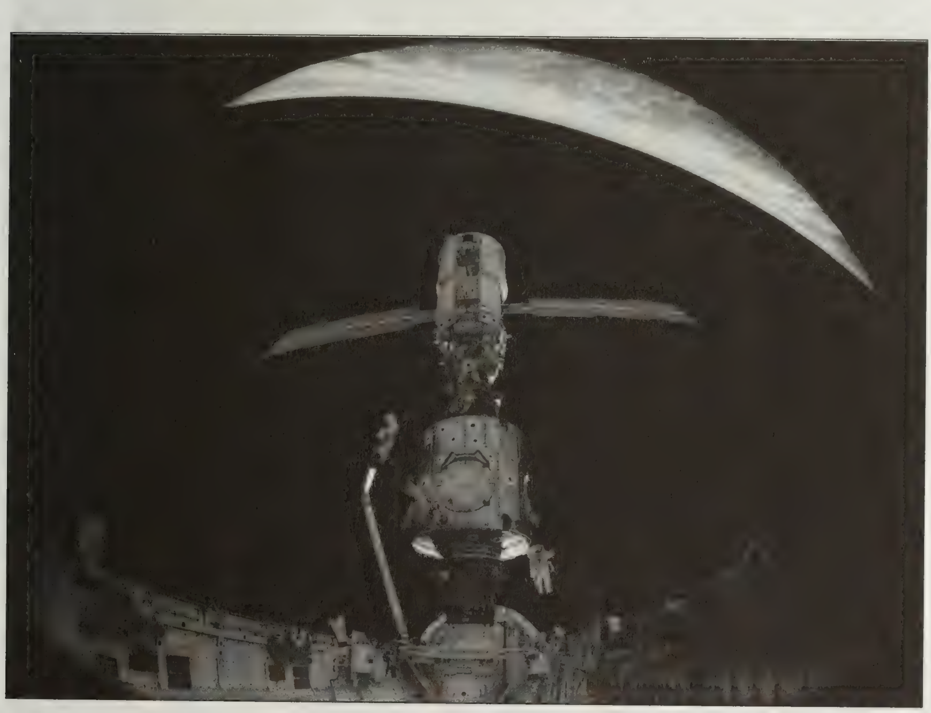


Figure 3–60. In December 1998, the crew of the STS-88 Mission began construction of the ISS, joining the U.S.-built Unity Node to the Russian-built Zarya Module. The crew used a large-format IMAX camera to take this photo, which shows astronauts Newman (left) and Ross maneuvering into position to continue work on Unity. (NASA Photo No. S99-03771)

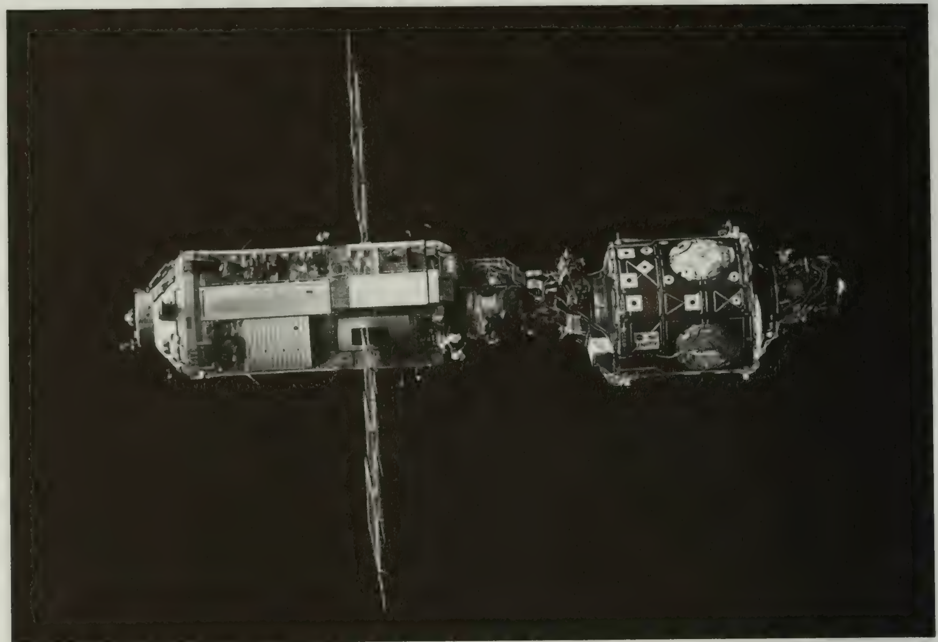


Figure 3–61. Unity and Zarya Modules. This photograph, taken during the STS-88 Mission, shows the connected Unity Module (Node 1) and Zarya (the Functional Cargo Block) after Unity's release from Endeavour*'s cargo bay. (NASA-MSFC Photo No. 0100335)*

Crew Return Vehicle

One of the requirements for the Space Station was a vehicle for returning crews to Earth in an emergency. In 1987, NASA Administrator James Fletcher requested $3 million from Congress for a study of a Crew Emergency Return Vehicle to be delivered to the Station by the Shuttle and used as a "lifeboat" to return stranded crew members. In October 1989, NASA issued a request for proposals for the renamed "Assured Crew Return Vehicle." Langley Research Center proposed a Crew Rescue Vehicle (CRV), called the HL-20, that could carry a crew of eight and would be carried by the VentureStar reusable launch vehicle. The HL-20 proved too expensive, and NASA instead awarded $1.5 million contracts to Lockheed and Rockwell International in 1990 to refine their concepts for a "lifting body" vehicle that would evolve into the X-38. At the time, a 1992 start was planned for hardware development.[193]

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[193] Harland and Catchpole, p. 119.

Figure 3–62. The complete ISS as envisioned in 1997 superimposed over the Straits of Magellan and the Mediterranean Sea. The drawing in Figure 3–63 (next page) shows the complete ISS with its components and the contribution of each component.

The X-38 project began in 1995 at Johnson Space Center using data from past lifting-body programs and the U.S. Army's Guided Precision Delivery Systems from Yuma Proving Grounds. The design closely resembled the X-24 wingless lifting body concept tested at Dryden Flight Research Center between 1969 and 1971. The vehicle would be able to return up to seven ISS crew members to Earth. In early 1996, a contract was awarded to Scaled Composites to construct two atmospheric test vehicles. Scaled Composites delivered the first vehicle, the V131, to Johnson Space Center in September 1996, where it was outfitted for its initial flight tests at Dryden Flight Research Center. The second vehicle, the V132, was delivered to Johnson Space Center in December 1996.

The test vehicles were shells made of composite materials such as fiberglass and graphite epoxy and strengthened with steel and aluminum at stress points. The test vehicle weights ranged from 15,000 pounds (6,804 kilograms) to about 25,000 pounds (11,340 kilograms). The prototypes were 23.5 feet (7.2 meters) long, 11.6 feet (3.5 meters) wide, and 8.4 feet (2.6 meters) high, approximately 80 percent the size of the proposed full-size CRV. The vehicles landed on skids, similar to the X-15 research aircraft, instead of wheels. The second test vehicle, the V132, carried a full flight control system, including electro-mechanical control surface actuators similar to those planned for the production CRV.

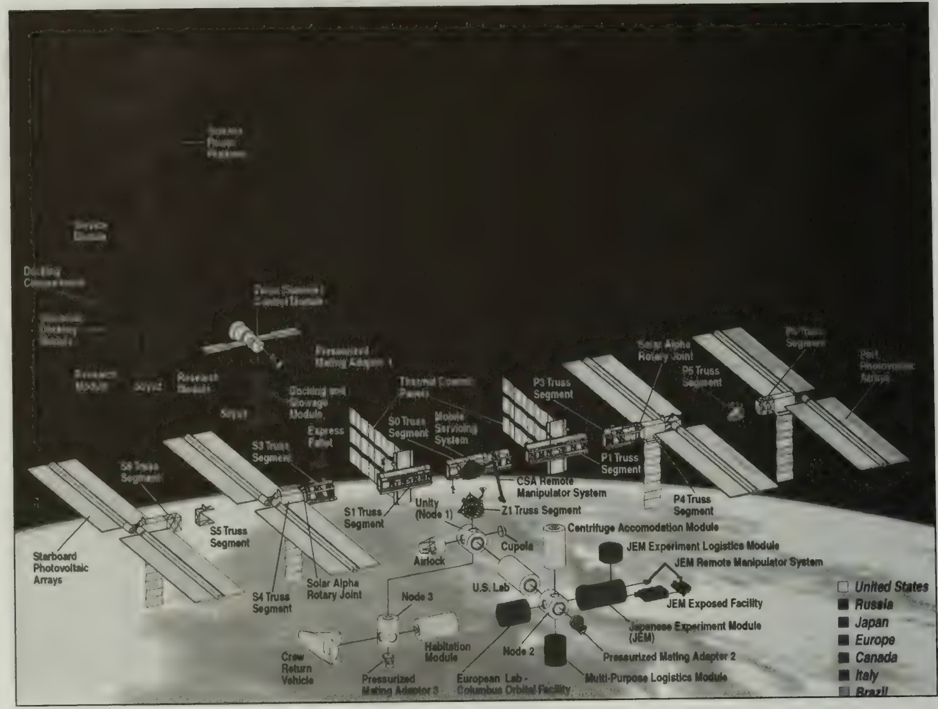
Service Module
Research Module
Soyuz
Research Module
Soyuz
Pressurized Mating Adapter 1
Docking and Stowage Module
Express Pallet
S3 Truss Segment
S6 Truss Segment
Thermal Control Panels
S0 Truss Segment
Mobile Servicing System
P3 Truss Segment
Solar Alpha Rotary Joint
P5 Truss Segment
P6 Truss Segment
Port Photovoltaic Arrays
P1 Truss Segment
CSA Remote Manipulator System
P4 Truss Segment
Z1 Truss Segment
Unity (Node 1)
S1 Truss Segment
S5 Truss Segment
Starboard Photovoltaic Arrays
Solar Alpha Rotary Joint
S4 Truss Segment
Airlock
Cupola
Centrifuge Accomodation Module
JEM Experiment Logistics Module
JEM Remote Manipulator System
U.S. Lab
Node 3
JEM Exposed Facility
Japanese Experiment Module (JEM)
Habitation Module
Node 2
Pressurized Mating Adapter 2
Crew Return Vehicle
Pressurized Mating Adaptor 3
European Lab - Columbus Orbital Facility
Multi-Purpose Logistics Module
☐ United States
■ Russia
■ Japan
■ Europe
■ Canada
■ Italy
■ Brazil

Figure 3–63. This drawing shows the completed ISS and contributions by each of the international partners, 1998. (NASA Photo No. S99-01389)

The unpiloted, captive-carry flight tests of the test airframes attached to B-52 aircraft began in July 1997 at Dryden Flight Research Center to study their aerodynamics while attached to the aircraft's wing pylon.[194] The first free-flight drop tests took place on March 12, 1998, and continued into 1999. The tests included use of a parafoil spanning 121.5 feet (37 meters) with an area of 5,500 square feet (511 square meters). These flight tests studied launch characteristics and assessed the operation of the parachute from deployment of the small drogue through reefing of the main parafoil and landing (see Figure 3–64, which shows the X-38 descending at the end of its first free flight on March 12, 1998). Drop tests used Navstar GPS signals for guidance. A production X-38 would weigh 20,000 pounds (9,072 kilograms), with its deorbit engine weighing 5,000 pounds (2,268 kilograms). The X-38 program was canceled in 2002 due to budget pressures associated with the ISS.[195]

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[194] This B-52 was the same aircraft used for the X-15 program.

[195] "X-38," NASA Fact Sheets, Dryden Flight Research Center, *http://www.nasa.gov/centers/dryden/news/FactSheets/FS-038-DFRC.html* (accessed May 24, 2005). Also Mark Lindroos, *Space Stations and Manned Spaceflight in the 1980s and 90s*, *http://www.abo.fi/~mlindroo/Station/Slides/index.htm,* "X-38 Crew Rescue Vehicle," *http://www.abo.fi/~mlindroo/Station/Slides/sld054.htm,* "HL-20 Crew Rescue Vehicle," *http://www.abo.fi/~mlindroo/Station/Slides/sld053.htm*, "NASA Assured Crew Return Vehicle," and *http://www.abo.fi/~mlindroo/Station/Slides/sld052.htm* (accessed May 23, 2005).

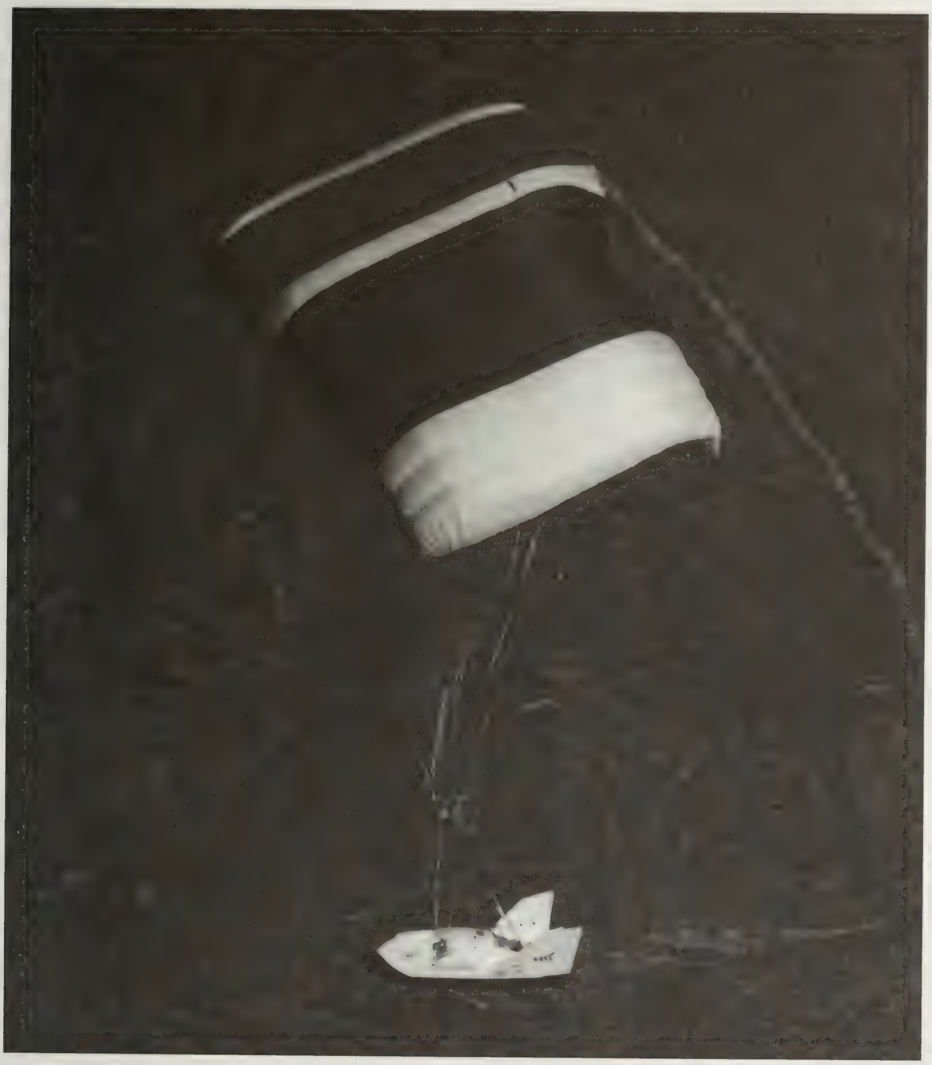

Figure 3–64. The X-38 descends under its steerable parafoil over the California desert during its first free flight at Dryden Research Center, March 12, 1998. (NASA-DFRC Photo No. EC98-44452-2)

Table 3–1. Percent of NASA's R&D or HSF Budget Allocated for Space Station

Year (Fiscal)	Space Station Appropriation (in thousands of dollars)	Percent of R&D or HSF Appropriation
1989	900,000	21
1990	1,800,000	33
1991	1,900,000	34
1992	2,929,000	32
1993	2,100,000	30
1994	2,100,000	27
1995	2,100,000	38
1996	2,144,000[a]	39
1997	1,840,200[b]	34
1998	2,351,300	42

[a] Marcia S. Smith, *Space Stations,* (Washington, DC: Congressional Research Service, The Library of Congress, 1999), p. CRS-10. Neither the appropriations bill (*Making Appropriations for Fiscal Year 1996 To Make a Further Downpayment Toward a Balanced Budget, and for Other Purposes,* Public Law 104-134, 104th Congress, 1st sess, [April 26, 1996]), nor Conference Report H. Rept.104-537 for FY 1996, provided any figure at all for the Space Station.

[b] Authorized amount; no amount for the Space Station specified in appropriations bill.

Table 3–2. *Authorized/Appropriated Budget (FY 1989–FY 1998)*
(in thousands of dollars)

	1989	**1990**	**1991**	**1992**	**1993**	**1994**
Research and Development Appropriation[a]	4,191,700	5,366,050	5,600,000	6,413,800	7,089,300	7,509,300
Space Station Authorization	900,000	1,800,000	2,907,000[b]	2,028,900[c]	2,100,000	1,900,000[d]
Space Station Appropriation[e]	900,000	1,800,000[f]	1,900,000[g]	2,029,000[h]	2,100,000	2,100,000[i]
	1995	**1996**	**1997**	**1998**		
HSF Appropriation[j]	5,573,900	5,456,600	5,362,900	5,506,500		
Space Station Authorization	2,120,900[k]	2,121,000[l]	1,840,200	2,121,300[m]		
Space Station Appropriation[n]	2,100,000[o]	2,144,000[p]	1,800,000	2,351,300[q]		
Russian Cooperation Authorization	150,100	100,000[r]	100,000	—[s]		

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[a] Authorized and appropriated amounts for individual life sciences and microgravity science categories were not included in budget bills, so they cannot be included in this table.

[b] House multiyear authorization bill was "laid aside." Senate multiyear authorization bill (S.916) was agreed to by House. Bill did not go to President for signature.

[c] Of this amount, $18 million was authorized for an Assured Crew Return Vehicle.

[d] Bill was passed by House and sent to the Senate, but the Senate never acted on it and there was no bill passed and signed by the President.

[e] From annual appropriations bills.

[f] Of this amount, $750 million was not to be available until June 1, 1990.

[g] Not in H.R. 5158. Added in Conference Committee, October 25, 1990, and signed into law, Public Law 101-507.

[h] Amount was specified in Conference Report, October 2, 1991, and was not included in text of appropriations bill. A stated appropriated amount that was greater than the authorized amount was most likely due to rounding in the appropriations budget document.

[i] Appropriated "space station activities, including payloads" as stated in Conference Report on H.R. 2491, House of Representative, October 4, 1993. Of this amount, no more than $160,000,000 million was to be available for termination costs connected with Space Station *Freedom* contracts, no more than $172,000,000 million was to be for Space Station operations and utilization capability development, and no more than $99,000,000 million was to be for supporting development. Of the total amount appropriated for the Space Station, not more than $1,100,000,000 billion was to be made available before March 31, 1994. Not more than $100,000,000 million was to be used to support cooperative space ventures between the United States and Russia, of which no more than $50,000,000 million was to be only for space transportation capability development activities and $50,000,000 million was to be only for space science activities other than life sciences.

[j] Space Shuttle appropriations are included in chapter 2, Launch Systems, of this volume. The HSF appropriation began to be used for the Space Station and Space Shuttle budgeted amounts except for a small amount allocated to the Space Station through the Science, Aeronautics and Technology appropriation.

[k] An amendment to the authorization bill required the NASA Administrator to submit a five-year program plan that showed "the total amount of estimated expenditures and proposed appropriations necessary to support the programs, projects, and activities…" The authorization bill was passed by both the House and Senate but was not sent to the President for signature. The authorization bill was passed October 5, 1994, after passage of the appropriations bill (September 28, 1994).

[l] The *International Space Station Authorization Act of 1995*, (H.R. 1601, 104th Congress, 1st sess.) authorized appropriations for the ISS for FY 1996 "and all subsequent fiscal years…through fiscal year 2002…." It specified that the total amount authorized not exceed $13,141,000,000 billion, and that amount was "to remain available until expended, for complete development and assembly of, and to provide for initial operations…of the International Space Station." The bill authorizing Space Station appropriations was separate from the bill authorizing all other NASA appropriations. The bill was referred to the Senate Commerce Committee but did not become law.

[m] The authorization bill passed by the House was referred to the Senate Committee where it remained.

[n] From annual appropriations bills.

[o] The amount of $2.1 billion appropriated for the Space Station was stated in the Conference Report on H.R. 4624, Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriations Act of 1995 (House of Representatives–September 12, 1994) that accompanied the bill signed by the President. The amount was not directly stated in the appropriations bill. This Congress, the 103rd, defeated five attempts to terminate the Space Station program in NASA funding bills, and three other attempts in broader legislation. The amount of $2.113 billion was stated in Marcia S. Smith, *Space Stations*, IB93017, updated December 12, 1996, CRS Issue Brief, *http://www.fas.org/spp/civil/crs/93-017.htm#legn* (accessed June 25, 2005).

[p] Smith, *Space Stations*, 1999, p. CRS-10. Neither the appropriations bill (*Making Appropriations for Fiscal Year 1996 To Make a Further Downpayment Toward a Balanced Budget, and for Other Purposes,* Public Law. 104-134, 104th Congress, 1st sess, (April 26, 1996)) nor conference report H. Rept.104-537 for FY 1996 gives any figure at all for the Space Station.

[q] The appropriations act stated that only $1.5 billion should be made available before March 31, 1998. The amount of $2,351,300,000 billion for the Space Station was introduced in House Report 105-297. This exceeded the authorized ceiling of $2.1 billion by $230 million but was below the $430 million requested by NASA. It was agreed that the appropriation would include "$80,000,000 from funds in the mission support account identified by the Agency ($25,000,000 from the Tracking and Data Relay Satellite (TDRS), $20,000,000 from environmental programs, $30,000,000 from Research Operations Support, and $5,000,000 from facilities), $100,000,000 in addition to the Agency's request, and $50,000,000 by reallocation from within the amounts requested in the Human Space Flight account."

[r] The authorization for Russian Cooperation was in a separate bill from the Space Station authorization. H.R. 2405, 1st session, 104th Congress, "National Aeronautics and Space Administration Authorization Act of 1995" was passed by the House and sent to the Senate. No action was taken by the Senate.

[s] Budget category not shown in authorization or appropriation bill.

Table 3–3. Programmed Budget (FY 1989–1998) (thousands of dollars)[a]

	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**
Research and Development					HSF					
Spacelab[b]	87,600	93,700	129,300	99,200	112,800	125,500	90,000	86,700	40,100	9,100
Space Station (Total)	900,000	1,749,623	1,900,000	—	2,162,000	1,939,200	1,889,600	2,143,600	2,148,600	2,331,300
U.S./Russian Cooperative Program and Program Assurance	—	—	—	—	—	70,800	50,100	—	—	—
Russian Space Agency Contract Support/U.S.-Russian Cooperation	—	—	—	—	—	100,000	100,000	100,000	100,000	—
Mir Support	—	—	—	—	—	70,800	50,100	—	—	—
Russian Program Assurance	—	—	—	—	—	—	—	—	200,000	110,000
Space Station Development	842,000	1,661,223	1,790,700	1,996,745	2,125,000	1,918,200	1,749,400	1,746,200	1,809,900	1,604,800
Development–Management and Integration	187,700	—	—	—	—	—	—	—	—	—

Table 3–3. *Programmed Budget (FY 1989–1998) (thousands of dollars)*[a] *(Continued)*

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Development–Pressurized Modules	155,500	—	371,200	—	—	—	—	—	—	—
Development–Assembly Hardware/Subsystems	267,200	—	731,200	—	—	—	—	—	—	—
Development–Platforms and Servicing	51,200	—	2,800	—	—	—	—	—	—	—
Development–Power Systems	124,000	—	292,800	—	—	—	—	—	—	—
Development–Operations/Utilization Capability	56,400	—	149,800	—	—	—	—	—	—	—
Development–Flight Hardware	—	—	—	—	2,085,500	1,609,700	1,319,900	1,468,900	1,540,700	1,461,000
Development–Test, Manufacturing and Assembly	—	—	—	—	—	99,000	91,900	73,500	95,700	97,400
Development–Operations Capability and Construction	—	—	—	—	—	151,000	169,800	112,600	115,700	—

Table 3–3. Programmed Budget (FY 1989–1998) (thousands of dollars)[a] *(Continued)*

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Development–Transportation Support	—	—	—	—	25,700	58,500	117,600	63,500	55,700	45,500
Development–Flight Technology Demonstrations	—	—	—	—	—	—	30,000	12,900	2,100	900
Development–Operations Capability and Construction	—	—	—	—	13,800	—	20,200	14,800	—	—
Assured Crew Return Vehicle	—	—	—	6,000	7,000	—	—	—	—	—
Flight Telerobotic System/Servicer	46,000	79,400	—	—	—	—	—	—	—	—
Space Station Utilization	—	—	—	—	30,000	21,000	31,300	—	—	—
Space Station Operations	—	—	—	—	—	—	108,900	120,000	142,600	500.200
Shuttle/Spacelab Payload Mission Management and Integration	—	—	—	—	94,100	108,700	102,300	53,600	24,200	—

Table 3–3. Programmed Budget (FY 1989–1998) (thousands of dollars)[a] *(Continued)*

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Space Station Integration Planning and Attached Payloads	8,000	9,000	3,000	—	—	—	—	—	—	—
Space Station Research	—	—	—	—	—	—	—	277,400	196,100	226,300
Space Station Transition Definition/ Advanced Programs	12,000	9,000	3,000	—	—	—	—	—	—	—
Life Sciences	79,100	106,051	137,400	157,650	139,500	186,800	140,500	109,600	—	—
Life Sciences Flight Experiments	—	—	—	94,700	—	—	—	—	—	—
Human Spaceflight and Systems Engineering	28,600	40,678	58,300	—	—	—	—	—	—	—
Space Biological Sciences	10,100	21,067	22,800	—	—	—	—	—	—	—
Life Sciences Research and Analysis	38,200	40,306	44,800	50,700	52,900	55,100	50,700	55,200	—	—

Table 3–3. Programmed Budget (FY 1989–1998) (thousands of dollars)[a] (Continued)

	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Life and Microgravity Sciences (Total)	—	—	—	157,650	407,500	—	467,400	304,200	243,700	—
Centrifuge	—	—	—	—	5,500	—	—	—	—	—
Search for Extraterrestrial Intelligence	2,200	4,000	11,500	12,250	—	—	—	—	—	—
Life Sciences Flight Program	—	—	—	—	81,100	—	89,800	54,400	—	—
Advanced Human Support Technology	—	—	—	—	—	—	—	—	19,700	—
Biomedical Research and Countermeasures Program	—	—	—	—	—	—	—	—	44,100	—
Gravitational Biology and Ecology Program	—	—	—	—	—	—	—	—	33,600	—

[a] Empty cells indicate that no programmed amounts were shown in the annual budget. See the individual budget tables that follow for additional details.

[b] Included in the Space Transportation Capability Development budget category.

Table 3–4. Spacelab Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	80,400/88,600	87,600
1990	98,900/95,600	93,700
1991	130,700/129,300	129,300
1992	150,200/96,000	99,200
1993	122,600/114,459	112,800
1994	139,900/125,500	125,500
1995	92,300/98,600	90,000
1996	97,000/86,700	86,700
1997	62,400/50,300	40,100
1998	14,200/11,900	9,100

Table 3–5. Space Station (Total) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Appropriation	Programmed	Budget Authority (Full Cost)
1989	967,400/900,000	900,000	900,000	900,000	n/a
1990	2,050,200/1,749,623	1,800,000	1,800,000	1,749,623	n/a
1991	2,451,000/1,900,000[a]	2,907,000	1,900,000	1,900,000	n/a
1992	2,028,900/2,028,900	2,028,900	2,029,000	—[b]	n/a
1993	2,250,000/2,122,467	2,100,000	2,100,000	2,162,000	n/a
1994[c]	—/1,937,000	1,900,000	2,100,000	1,939,200	2,106,000
1995	1,889,600/1,889,600	1,889,600	2,100,000	1,889,600	2,112,900
1996	1,833,600/1,863,600	2,121,000	2,144,000[d]	2,143,600	2,143,600
1997	1,802,000/2,148,600	1,840,200	1,800,000	2,148,600	2,148,600
1998	2,121,300/2,501,300	2,121,300	2,351,300	2,331,300	2,121,300

[a] Congress reduced the FY 1991 funding requested for the Space Station by $551.0 million. A study to restructure the program was incomplete and did not allow for sufficient definition of requirements to develop detailed estimates.

[b] Program was being restructured and no programmed amount was shown.

[c] Space Station Freedom program was budgeted within the Office of Space Systems Development.

[d] Smith, *Space Stations*, 1999, p. CRS-10. Neither the appropriations bill (*Making Appropriations for Fiscal Year 1996 To Make a Further Downpayment Toward a Balanced Budget, and for Other Purposes,* Public Law 104-134, 104th Congress, 1st sess, (April 26, 1996)), nor conference report H. Rept.104-537, gives any figure at all for the Space Station for FY 1996.

Table 3–6. U.S./Russian Cooperative Program Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization	Programmed	Budget Authority (Full Cost)
1994	—[a]	—	70,800	70,800
1995	—/50,100	50,100	50,100	50,100
1996	29,200/29,200	100,000	—	29,200
1997	38,200/50,000	100,000/100,000	—[b]	38,200

[a] Budget category not established at time of budget submission.

[b] Budget line item was discontinued. New budget line item, U.S./Russian Cooperation and Program Assurance, was established.

Table 3–7. Russian Space Agency Contract Support[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—	100,000
1995	—[b]/100,000	100,000
1996	100,000/100,000	100,000
1997	100,000/100,000	300,000[bc]
1998	—/50,000	—

[a] Changed to U.S./Russian Cooperation and Program Assurance budget category in FY 1998 budget.

[b] Budget category not established at time of initial budget submission.

[c] Consisted of $100,000,000 million from the disestablished budget category of U.S./Russian Cooperative Program and $200,000,000 million reallocated from elsewhere within the HSF account.

Table 3–8. Mir *Support Funding History (in thousands of dollars)*

Year (Fiscal)	Submission	Programmed
1994	—[a]	70,800
1995	—/50,100	50,100
1996	29,200/29,200	—
1997	38,200/—	—

[a] Budget category not established at time of budget submission.

Table 3–9. Russian Program Assurance Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1997	—[a]	200,000
1998	—/50,000	110,000

[a] No budget category at time of budget submission.

Table 3–10. Space Station Development Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1989	935,400/842,000	842,000	n/a
1990	1,970,200/1,661,223	1,661,223	n/a
1991[a]	2,299,800/—[b]	1,790,700	n/a
1992	—[c]/2,022,900	1,996,745	n/a
1993	2,200,000/2,115,467	2,125,000[d]	n/a
1994	—[e]/1,911,000	1,918,200	1,918,200
1995	1,662,000[f]/ 1,752,400[g]	1,749,400	1,749,400
1996	1,612,800[h]/1,696,200	1,746,200	1,746,200
1997	1,513,200/1,766,300	1,809,900	1,766,300
1998	1,386,100/1,789,900	1,604,800[i]	1,386,100

[a] The distribution by program element (Development, Flight Telerobotic Servicer, Operations, and Advanced Programs) for the FY 1991 revised estimate and the FY 1992 budget estimate were under review, pending the preliminary results of the 90-day study to restructure the Space Station program, directed by the conference report accompanying the FY 1991 *Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriations Act, 1991,* Public Law 101-507, 101st Congress, 2nd sess, (November 5, 1990).

[b] No revised budget submitted shown.

[c] The FY 1992 budget estimate was submitted before completion of the Space Station restructuring activity, and no project estimates were available.

[d] Included $13,800,000 million for construction of facilities.

[e] No initial budget estimate shown for this category.

[f] Included $20,200,000 million for construction of facilities.

[g] Included $20,200,000 million for construction of facilities.

[h] Included $14,800,000 million for construction of facilities.

[i] Budget category was renamed "Vehicle."

Table 3–11. Development–Management and Integration Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	169,400/187,700	187,700
1990	230,200/198,258	—[a]
1991	248,000/—	—

[a] No programmed amount shown.

Table 3–12. Development–Pressurized Modules[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	188,000/155,500	155,500
1990	366,000/303,900	—
1991	522,100/—	371,200
1992	—/433,500	—
1993	448,400/—	—[b]

[a] Consisted of Work Package 1, managed by Marshall Space Flight Center.

[b] No programmed amounts shown. Work packages were restructured into other budget categories with restructuring of program.

Table 3–13. Development–Assembly Hardware/Subsystems[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	288,000/263,200	267,200
1990	762,000/666,300	—[b]
1991	872,600/—	731,200
1992	—/764,600	—
1993	766,200/—	—[c]

[a] Consisted of Work Package 2, managed by Johnson Space Center.

[b] No programmed amounts shown.

[c] No programmed amounts shown.

Table 3–14. Development–Platforms and Servicing[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	56,000/51,200	51,200
1990	130,000/107,500	—
1991	34,100/—[b]	2,800[c]

[a] Consisted of Work Package 3, managed by Goddard Space Flight Center.

[b] All activities associated with this budget category were eliminated in the 1991 restructuring.

[c] Costs associated with termination of contracts.

Table 3–15. Development–Power Systems[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	154,000/120,000	124,000
1990	298,000/249,925	—[b]
1991	—/367,900	292,800
1992	—/306,500	—[c]
1993	350,400	—

[a] Consisted of Work Package 4, managed by Lewis Research Center.

[b] No programmed amount shown.

[c] No programmed amount shown.

Table 3–16. Development–Operations/Utilization Capability Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	80,000/64,400	56,400
1990	184,000/135,340	—[a]
1991	255,100	149,800
1992	—/253,600	—[b]
1993	377,100/—	—

[a] No programmed amount shown.

[b] No programmed amount shown.

Table 3–17. Development–Flight Hardware Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	2,085,500
1994	—/1,642,400	1,609,700
1995	1,127,000/1,319,900	1,319,900
1996	1,277,200/1,413,300	1,468,900
1997	1,244,400/1,480,500	1,540,700
1998	1,157,900/1,529,000	1,461,000

[a] Budget category introduced with the redesigned Space Station. Budget categories were restructured.

Table 3–18. Development–Test, Manufacturing and Assembly Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]/87,600	99,000
1995	117,000/94,900	91,900
1996	90,300/68,600	73,500
1997	78,200/97,300	95,700
1998	93,600/97,400	97,400

[a] Budget category introduced with the redesigned Space Station, not at time of initial budget submission. Budget categories were restructured.

Table 3–19. Development–Operations Capability and Construction Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]/151,000	151,000
1995	257,800/169,800	169,800
1996	137,100/117,100	112,600
1997	111,300/130,700	115,700
1998	85,400/115,100	—

[a] Budget category introduced with the redesigned Space Station, not at time of initial budget submission. Budget categories were restructured.

Table 3–20. Development–Transportation Support Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	25,700
1994	—/30,000	58,500
1995	100,000/117,600	117,600
1996	83,000/74,100	63,500
1997	76,100/55,700	55,700
1998	47,800/47,000	45,500

[a] Budget category introduced with the redesigned Space Station. Budget categories were restructured.

Table 3–21. Development–Flight Technology Demonstrations Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1994	—[a]	—
1995	40,000/30,000	30,000
1996	10,400/8,300	12,900
1997	3,200/2,100	2,100
1998	1,400/1,400	900

[a] Budget category was introduced with the redesigned Space Station. Budget categories were restructured.

Table 3–22. Development–Operations Capability and Construction Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	13,800
1994	—/—	—
1995	20,200/20,200	20,200
1996	14,800/14,800	14,800[b]

[a] Budget category introduced with the redesigned Space Station. Budget categories were restructured. Included in Construction of Facilities appropriation.

[b] Included with Operations beginning with FY 1997.

Table 3–23. Shuttle/Spacelab Payload Mission Management and Integration Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Programmed
1993[b]	101,100/94,018	94,100
1994	117,700[c]/111,500	108,700
1995	112,400/113,900	102,300
1996	85,400/77,600	53,600
1997	54,400/24,200	24,200
1998	6,900/4,900[d]	—[e]

[a] This category included funds to manage the mission planning, integration, and execution of all NASA Spacelab and attached Shuttle payloads.

[b] Transferred to OLMSA program.

[c] Included in OLMSA budget.

[d] Changed to Mission Integration Function in OLMSA realignment of budget categories that occurred with FY 1999 congressional budget submission (and revisions to FY 1998 budget submission).

[e] No programmed funds in this budget category. Included with OLMSA funds.

Table 3–24. Space Station Integration Planning and Attached Payloads Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	8,000	8,000
1990	23,000/4,975	4,975
1991	15,000/3,000	3,000
1992	—[a]	—[b]

[a] Functions associated with Space Station Integration Planning were transferred to the Materials Processing budget category beginning in FY 1992.

[b] No programmed funds in this budget category.

Table 3–25. Assured Crew Return Vehicle Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1992	—[a]	6,000
1993	15,000/7,000	7,000
1994	—/5,000	—
1995	—[b]	—

[a] Budget category not established at time of budget submission.

[b] The redesigned Space Station was to use an Assured Crew Return Vehicle based on a Soyuz vehicle and launched on a Russian booster for rescue and crew rotation. The Soyuz Assured Crew Return Vehicle was a Russian element of the Space Station and required no U.S. funding in FY 1995.

Table 3–26. Flight Telerobotic System/Servicer Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	20,000/46,000	46,000
1990	15,000[a]/79,400[b]	79,400
1991	106,300/—[c]	—

[a] NASA was actively pursuing approaches to encourage the private sector to invest in the Flight Telerobotic Servicer (FTS). The requested funding was to provide for supporting development activities.

[b] After consideration of industry responses, a decision was made that the FTS was not a viable candidate for full commercial development. The increased budget estimate was consistent with the decision to provide for a NASA procurement through a prime contractor.

[c] All activities associated with this budget category were eliminated in the 1991 restructuring.

Table 3–27. Space Station Utilization Support Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	30,000
1994	—/21,000	21,000
1995	96,600/28,300	31,300
1996	67,900/47,400	—[b]
1997	72,100/—	—

[a] Budget category not established at time of budget submission.

[b] Budget category disestablished; included with Space Station Research budget category beginning in FY 1997.

Table 3–28. Space Station Operations Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1990	25,000/—[a]	—	n/a
1991	8,900/—[b]	—	n/a
1992	—	—	n/a
1993	35,000/—	—	n/a
1994	—	—	n/a
1995[c]	131,000/108,900	108,900	108,900
1996	152,900/120,000	120,000	120,000
1997	216,700/177,600	142,600	177,600
1998	490,100/490,100	500,200[d]	490,100

[a] Deletion of the requested amount reflected a delay due to program rephasing associated with the rebaselining activities of the configuration baseline review, which indicated that FY 1990 resources would not be required to meet the revised program milestones.

[b] Amounts designated for Space Station Operations were deferred or canceled as the Space Station schedule slipped.

[c] Space Station Operations budget category included vehicle operations and ground and transportation operations.

[d] Included construction of facilities.

Table 3–29. Space Station Research[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)[b]
1994	—[c]	—[d]	187,800
1995	—	—	254,600
1996	—	277,400	277,400
1997	—/204,700	196,100	204,700
1998	245,100/221,300	226,300	245,100

[a] Included *Mir* research and support, utilization support, research facilities, science utilization (HSF), and science utilization (Construction of Facilities).

[b] Reflected amounts used for Space Station activities from Science, Aeronautics, and Technology appropriation and from Research and Development and Construction of Facilities appropriations.

[c] Budget category not established.

[d] No programmed amount in HSF appropriation. Full cost budget authority included Space Station Research amounts from other appropriation categories (Science, Aeronautics, and Technology and former appropriation categories of Research and Development and Construction of Facilities).

Table 3–30. Space Station Transition Definition/Advanced Programs Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	12,000/12,000	12,000
1990	25,000/9,000[a]	9,000
1991	36,000	3,000

[a] Name of budget category was changed to Advanced Programs, consisting of advanced system studies, advanced development, and support for human exploration.

Table 3–31. Life Sciences Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	101,700	79,100
1990	124,200/106,278	106,051
1991	163,000/138,000	137,400
1992	183,900/145,800	157,650
1993	177,200/140,550	139,500
1994	143,900/188,200[a]	186,800
1995	145,600/140,700	140,500
1996	—[b]/136,400	109,600
1997	144,300/97,400	—[c]
1998	85,500/[d]	—[e]

[a] Realignment of budget categories. Life Sciences under the Office of Space Science moved to OLMSA. OLMSA had programs for Life Sciences and Microgravity Science Research, Shuttle/Spacelab Payload, and Mission Management and Integration, and corresponding budget categories.

[b] Became subcategory under OLMSA. Included Research and Analysis and Flight Program budget categories. No initial submission for this budget category.

[c] No programmed amount shown.

[d] Realigned to Advanced Human Support Technology Program, Biomedical Research and Countermeasures Program, and Gravitational Biology and Ecology Program.

[e] No programmed amount shown.

Table 3–32. Life Sciences Flight Experiments Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	54,500/—[a]	—
1990	—	—
1991	—	—
1992	—	94,700
1993	89,700[b]/81,089	—
1994	94,700/—[c]	—

[a] Budget category appeared in initial submission for FY 1989 budget but not in revised budget or in programmed amount. This budget category did not reappear in the budget until the FY 1993 budget submission (which also listed the FY 1992 programmed amount).

[b] Moved to Space Applications Microgravity Flight Experiments.

[c] Budget category disestablished. No submission or programmed amount shown.

Table 3–33. Human Spaceflight and Systems Engineering Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	—[a]	28,600
1990	42,800/40,678	40,678
1991	71,000/58,300	58,300
1992	58,600/70,100[b]	—
1993	71,400/—[c]	—

[a] Budget category not established at time of budget submission.
[b] Included all Spacelab flight program activities.
[c] Budget category disestablished. No submitted or programmed amount for this category shown.

Table 3–34. Space Biological Sciences Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	—[a]	10,100
1990	27,600/21,200	21,067
1991	32,000/22,800	22,800
1992	31,100/14,600	—[b]
1993	18,300/—	—

[a] Budget category not established at time of budget submission.
[b] Budget category disestablished. No further funds requested or programmed.

Table 3–35. Life Sciences Research and Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	47,200/38,200	38,200
1990	47,000/40,400	40,306
1991	47,900/44,800	44,800
1992	64,700/47,600	50,700
1993[a]	55,600/53,940	52,900
1994	49,200/55,100	55,100
1995	51,900/50,700	50,700
1996[b]	50,400/55,200	55,200
1997	49,800/58,000	—[c]
1998	50,000/—	—

[a] Moved to Space Applications Microgravity Research and Analysis.
[b] Became Research and Analysis dealing specifically with Life Sciences programs under OLMSA.
[c] Budget category disestablished. No funds requested or programmed for this budget category.

Table 3–36. Lifesat/Radiation Biology Initiative History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1992	15,000/—[a]	—

[a] All funding for the Lifesat program was deleted per congressional direction. The program was additionally reduced by $5 million as part of the congressionally-directed general reduction to space science and applications.

Table 3–37. Life and Microgravity Sciences (Total) Funding History (in thousands of dollars)[a]

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)[b]
1992	—[c]	157,650[d]	n/a
1993	177,200/140,550	407,500	n/a
1994	351,000/515,300[e]	—[f]	96,000
1995	470,900/—	467,400	158,200
1996	—/488,500	304,200	210,800
1997	498,500/243,700	243,700	267,800
1998	214,200/214,200	—[g]	345,000

[a] OLMSA combined several of the budget categories formerly from the Life Sciences budget category within the Office of Space Science and Applications, specifically from the Life Sciences and Materials Programs together with their supporting Spacelab management function. OLMSA consisted of Life Sciences, Microgravity Science Research, Shuttle/Spacelab Payload Mission Management and Integration, and Space Station Payload Facilities budget categories. Materials Processing, previously funded under Space Applications, was renamed Microgravity Research, and remained a distinct element within the new structure. The addition of the Shuttle/Spacelab Payload Mission Management and Integration, which was transferred from Physics and Astronomy, served to consolidate the on-orbit research in these disciplines together with their associated space access infrastructure.

[b] Did not include all Life and Microgravity Sciences activities. Included only items related to the Space Station. From FY 1994–FY 1998, these totaled: Space Station Facilities ($694,700,000 million), Life Sciences and Aerospace Medicine ($122,900,000 million), Microgravity Research ($158,500,000 million), and STS (Space Shuttle)/Spacelab Mission Management ($83,700,000 million).

[c] Office of Life and Microgravity Sciences and corresponding budget not established at this time.

[d] Former funding structure.

[e] Reflected new funding structure.

[f] No programmed amount shown.

[g] No programmed amount shown.

Table 3–38. Centrifuge Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	18,400/5,521	5,500[a]
1994	—[b]	—

[a] Centrifuge budget category was removed from Space Science budget.

[b] No funds were included in the FY 1994 request for the centrifuge facility. Funding plans were being reevaluated in accordance with NASA's reexamination of plans for the Space Station.

Table 3–39. Search for Extraterrestrial Intelligence Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	—[a]	2,200[b]
1990	6,800/4,000	4,000
1991	12,100/12,100	11,500
1992	14,500/13,500	12,250
1993	13,500/—[c]	—

[a] Budget category not established at time of budget submission.

[b] Funded as part of Research and Analysis budget category.

[c] The Search for Extraterrestrial Intelligence (SETI) program was deleted from the Space Life Science program. Technology developed under the program was incorporated in the Towards Other Planetary System (TOPS) program in the Planetary Exploration Research and Analysis program, in accordance with congressional direction. Per congressional direction, funding was terminated for SETI within the Life Sciences program.

Table 3–40. Life Sciences Flight Program Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	81,100
1994	—[b]/133,100	—[c]
1995	93,700/—[d]	89,800
1996[e]	—[f]/81,200	54,400
1997	56,400/39,400	—[g]

[a] Budget category was not included in FY 1993 budget submission.

[b] No initial budget submission shown for this budget category.

[c] No programmed amount shown.

[d] Budget category not listed in revised budget submission.

[e] Became Research and Analysis budget category dealing specifically with Life Sciences programs under OLMSA.

[f] No initial budget submission for this budget category.

[g] No programmed amount listed.

Table 3–41. Advanced Human Support Technology Program[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1997	—	19,700
1998	—[b]/17,900	—[c]

[a] Formerly Life Sciences budget category under the Office of Space Science.

[b] Budget category did not appear until revised budget request was submitted.

[c] No programmed amount shown.

Table 3–42. Biomedical Research and Countermeasures Program[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1997	—	44,100
1998	—/40,600	—

[a] Formerly Life Sciences budget category under the Office of Space Science.

Table 3–43. Gravitational Biology and Ecology Program[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1997	—	33,600
1998	—/30,000	—

[a] Formerly Life Sciences budget category under the Office of Space Science.

Table 3–44. Orbiter Characteristics

Component	Characteristics
Length	37.2 m (122.2 ft)
Height	~17 m (56.7 ft)
Vertical stabilizer	8 m (26.2 ft)
Wingspan	23.8 m (78.1 ft)
Body flap	
Area	12.6 sq m (135.6 sq ft)
Width	6.1 m (20 ft)
Aft fuselage	
Length	5.5 m (18 ft)
Width	6.7 m (22 ft)
Height	6.1 m (20 ft)
Mid fuselage	
Length	18.3 m (60 ft)
Width	5.2 m (17.1 ft)
Height	4.0 m (13.1 ft)
Airlock	
Inside diameter	160 cm (5.2 ft)
Length	211 cm (6.9 ft)
Minimum clearance	91.4 cm (3 ft)
Opening capacity	46 cm by 46 cm by 127 cm (1.5 ft by 1.5 ft by 4.2 ft)
Payload bay	4.6 m by 18.3 m (15 ft by 60 ft)
Forward fuselage crew cabin	71.5 cu m (2,525 cu ft)
Payload bay doors	
Length	18.3 m (60 ft)
Diameter	4.6 m (15.1 ft)
Surface area	148.6 sq m
Weight	1,480 kg (3,263 lb)
Wing	
Length	18.3 m (60 ft)
Maximum thickness	1.5 m (4.9 ft)
Elevons	4.2 m and 3.8 m (13.8 ft and 12.5 ft)
Tread width	6.9 m (22.7 ft)
Structure type	Semi-monocoque
Structure material	Aluminum
Gross takeoff weight	Variable depending on payload and on-board consumables
Nominal landing weight	Variable
Inert weight (approx.)	74,844 kg (165,003 lb)

Table 3–44. Orbiter Characteristics (Continued)

Component	Characteristics
Main engines	
Number	3
Average thrust (104%)	1,752 kN (393,800 lb) at sea level
Nominal burn time	522 seconds

Table 3–45. Endeavour *Construction Milestones*

Date	Milestone
February 15, 1982	Begins structural assembly of crew module
July 31, 1987	Contract awarded to Rockwell
September 28, 1987	Begins structural assembly of aft-fuselage
December 22, 1987	Wings arrive at Palmdale, California, from Grumman
August 1, 1987	Final assembly begins
July 6, 1990	Final assembly completed
April 25, 1991	Rollout from Palmdale, California
May 7, 1991	Delivery to Kennedy Space Center
April 6, 1992	Flight readiness firing
May 7, 1992	First flight (STS-49)

Table 3–46. Space Shuttle Payload Accommodation[a]

Location/Accommodation	Description
Payload Bay	
Attached	Attached payloads were generally large payloads (14.5 ft/4.4 m maximum diameter) mounted directly to the payload bay attach fittings on an "across the bay" structure.
Deployable/Retrieval	Deployable/retrievable payloads were offered the same basic set of services as attached payloads with extensions allowing for mate/demate with attach hardware, remote command, and control, etc.
Sidewall	The sidewall payloads mounted to the orbiter's sidewall.
Payload Carriers	
Spacelab Pallet	Spacelab pallets were U-shaped platforms for mounting payloads. The pallets had hard points for mounting heavy equipment. Each pallet could hold up to 3 tons (2,722 kg) if the weight was evenly distributed. Each pallet was 13 ft (3.9 m) wide and 10 ft (3 m) long.
Mission Peculiar Equipment Support Structure (MPESS)	The MPESS was an A-frame structure spanning the width of the payload bay. Payloads could be mounted on the top and sides of the structure.
GAS	The GAS carrier system accommodated payloads in canisters mounted in the Shuttle payload bay on the sidewall or on a cross-bay truss structure.
Hitchhiker	The Hitchhiker carrier was intended for payloads requiring power, data, and command services. Hitchhiker provided real-time data transfer for experimenters and crew control/display capability.
Hitchhiker-Jr.	The Hitchhiker-Jr. (HH-Jr.) carrier provided mechanical and electrical interfaces similar to the GAS carrier but had avionics to monitor carrier and payload functions and power services.

Table 3–46. Space Shuttle Payload Accommodation[a] (Continued)

Location/Accommodation	Description
SPARTAN	SPARTAN was a reusable, three-axis stabilized, free-flying carrier providing extended mission flight opportunities for a variety of scientific studies in low-Earth orbit. SPARTAN was taken into orbit by the Space Shuttle, deployed, and operated via ground commands. The satellite was retrieved either on the same Shuttle mission or on a later mission and returned to the ground for reuse.
Space Experiment Module (SEM)	SEM was a canister assembly providing self-contained structure, power, command, and data storage capabilities for microgravity experiments.
Crew Compartment	
Middeck	The middeck offered accommodations in a pressurized environment for payloads that could be stowed within a middeck locker or mounted on an adapter plate that replaced one or more lockers.
Pressurized Modules	
Spacelab	Spacelab modules added significant "shirtsleeve" workspace and laboratory facilities to the Space Shuttle. (See following sections.)
SPACEHAB	SPACEHAB modules also added significant "shirtsleeve" workspace and laboratory facilities to the Space Shuttle. (See following sections.)

[a] "Payload Accommodations and Services," *http://shuttlepayloads.jsc.nasa.gov/flying/accommodations/accommodations.htm* (accessed July 12, 2005).

Table 3–47. Spacelab Module Characteristics[a]

Item	Characteristic
Diameter	4.06 m (13.3 ft)
Module length (1 segment)	2.70 m (8.9 ft)
Module shell material	2219-T851 aluminum
Electrical power	28 VDC +/- 4 VDC
Internal ambient temperature	18°-27°C (64.4°-80.6°F)
Humidity	30%-70% relative humidity
Air leakage	1.3 kg/day max (2.9 lb)
Payload mass	4,500 kg (9,921 lb) (long module)
Payload volume	22.2 cu m (784 cu ft) (long module)
Electrical power to payload	3.9 kW continuous 6.5 kW peak
Other features of payload	Optical window Airlock

[a] E. Vallerani, "Pressurised Module Elements from Spacelab to Columbus," in *Spacelab, 1983–1993; Ten Years Experience in Cooperative Manned Space Activities*; Proceedings from the CEAS European Forum, October 1993, Florence, Italy (Washington, DC: American Institute of Aeronautics and Astronautics, 1993), p. 16.

Table 3–48. Spacelab Missions (1989–1998[a])

Mission	Date	Purpose	Configuration
Astro-1/STS-35	December 2, 1990	Astronomy	Igloo plus 2 pallets
Spacelab Life Sciences (SLS)-1/STS–40	June 5, 1991	Space life sciences	Long module
International Microgravity Laboratory (IML)-1/STS-42	January 22, 1992	Microgravity studies	Long module
Atmospheric Laboratory for Applications and Science (ATLAS)-1/STS-45	March 24, 1992	Atmospheric studies	Igloo plus 2 pallets
United States Microgravity Laboratory (USML)-1/STS-50	June 25, 1992	Microgravity studies	Long module/ extended duration orbiter
Spacelab J1/STS-47	September 12, 1992	Microgravity and life sciences	Long module
ATLAS-2/STS-56	April 8, 1993	Atmospheric studies	Igloo plus 1 pallet
Spacelab D2/STS-55	April 26, 1993	Microgravity studies	Long module plus U.S. Microgravity Laboratory
SLS 2 LM/STS-58	October 18, 1993	Life sciences	Long module/ extended duration orbiter
IML-2/STS-65	July 8, 1994	Microgravity	Long module/ extended duration orbiter
ATLAS-3/STS-66	November 3, 1994	Atmospheric Physics	Igloo plus 2 pallets
Astro-2/STS-67	March 2, 1995	Astronomy	Igloo plus 2 pallets, extended duration orbiter
Spacelab-*Mir* LM/ STS-71	June 27, 1995	Life sciences	Long module
USML-2/STS-73	October 20, 1995	Microgravity	Long module/ extended duration orbiter
Life and Microgravity Spacelab (LMS) 1/ STS-78	June 20, 1996	Life and microgravity sciences	Long module/ extended duration orbiter
Microgravity Science Laboratory (MSL)-1/ STS-83[b]	April 4, 1997	Materials sciences	Long module/ extended duration orbiter

Table 3–48. Spacelab Missions (1989–1998[a]) (Continued)

Mission	Date	Purpose	Configuration
MSL-1R/STS-94 (reflight of MSL-1)	July 1, 1997	Materials sciences	Long module/ extended duration orbiter
Neurolab/STS-90	April 17, 1998	Neurobiological life sciences	Long module/ extended duration orbiter

[a] "Spacelab," European Space Agency, *http://www.esa.int/esapub/achievements/Sc72s4.pdf* (accessed July 22, 2005).

[b] Shortened mission due to concerns about one of the three fuel cells. Reflown on STS-94.

Table 3–49. SPACEHAB Missions[a]

Mission	Date	Payload
STS-57	June 21, 1993	SPACEHAB Module
STS-60	February 3, 1994	SPACEHAB Module
STS-63	February 3, 1995	SPACEHAB Module
STS-76	March 22, 1996	SPACEHAB Module
STS-77	May 19, 1996	SPACEHAB Module
STS-79	September 16, 1996	Logistics Double Module
STS-81	January 12, 1997	Logistics Double Module
STS-84	May 15, 1997	Logistics Double Module
STS-86	September 25, 1997	Logistics Double Module
STS-89	January 22, 1998	Logistics Double Module
STS-91	June 2, 1998	Logistics Single Module/ SPACEHAB Universal Communications System
STS-95	October 29, 1998	SPACEHAB Module

[a] "Past Missions," SPACEHAB, *http://spacehab.com/missions/past_shi.htm* (accessed July 5, 2005).

Table 3–50. Space Shuttle Extravehicular Activity (1989–1998[a])

Mission	Date	Astronaut	Individual EVA Time per Astronaut	Cumulative Time in Space	Description
STS-37	April 7, 1991	Ross and Apt	4 hr, 26 min	20 hr, 26 min	Deploy jammed Gamma Ray Observatory high-gain antenna
	April 8, 1991	Ross and Apt	5 hr, 47 min		Test Crew and Equipment Translation Aid cart and other EVA equipment
STS-49	May 10, 1992	Thuot and Hieb	3 hr, 43 min	50 hr, 52 min	Unsuccessful attempt to retrieve INTELSAT VI satellite and install perigee kick motor
	May 11, 1992	Thuot and Hieb	5 hr, 30 min		Unsuccessful attempt to retrieve INTELSAT VI satellite and install perigee kick motor
	May 13, 1992	Thuot, Hieb, and Akers	8 hr, 29 min		Retrieve INTELSAT VI satellite and install perigee kick motor
	May 14, 1992	Thornton and Akers	7 hr, 44 min		Test equipment for Space Station Freedom program (assembly of Station by EVA Methods experiment)
STS-54	January 17, 1993	Runco and Harbaugh	4 hr, 28 min	8 hr, 56 min	ISS preparation (Detailed Test Objective)
STS-57	June 25, 1993	Low and Wisoff	5 hr, 50 min	11 hr, 40 min	Hubble Space Telescope preparation (Detailed Test Objective), European Retrievable Carrier (EURECA) antenna stow

Table 3–50. Space Shuttle Extravehicular Activity (1989–1998[a]) (Continued)

Mission	Date	Astronaut	Individual EVA Time per Astronaut	Cumulative Time in Space	Description
STS-51	September 16, 1993	Newman and Walz	7 hr, 5 min	14 hr, 10 min	Hubble Space Telescope preparation (Detailed Test Objective)
STS-61	December 4, 1993	Musgrave and Hoffman	7 hr, 54 min	70 hr, 56 min	First Hubble Space Telescope servicing; prepare worksite, change gyroscopes, fuse plugs
	December 5, 1993	Akers and Thornton	6 hr, 36 min		Replace Hubble Space Telescope solar arrays
STS-61	December 6, 1993	Musgrave and Hoffman	6 hr, 47 min		Replace Wide Field and Planetary Camera (WF/PC) with Wide Field Planetary Camera-2 (WFPC-2)
	December 7, 1993	Akers and Thornton	6 hr, 50 min	70 hr, 56 min	Install Corrective Optics Space Telescope Axial Replacement (COSTAR) system
	December 8, 1993	Musgrave and Hoffman	7 hr, 21 min		Replace solar array drive electronics
STS-64	September 16, 1994	Lee and Meade	6 hr, 51 min	13 hr, 42 min	Simplified Aid for EVA Rescue (SAFER) test
STS-63	February 9, 1995	Foale and Harris	4 hr, 39 min	9 hr, 18 min	EVA Development Flight Test (EDFT) (SPARTAN Mass Handling)
STS-69	September 16, 1995	Voss and Gernhardt	6 hr, 46 min	13 hr, 32 min	EDFT (task board with ISS EVA interfaces)

Table 3–50. Space Shuttle Extravehicular Activity (1989–1998[a]) (Continued)

Mission	Date	Astronaut	Individual EVA Time per Astronaut	Cumulative Time in Space	Description
STS-72	January 15, 1996	Chiao and Barry	6 hr, 9 min	26 hr, 6 min	EDFT (ISS assembly and maintenance hardware)
	January 17, 1996	Chiao and Scott	6 hr, 54 min		EDFT (ISS assembly and maintenance hardware); test EMU thermal modifications
STS-76	March 27, 1996	Clifford and Godwin	6 hr, 2 min	12 hr, 4 min	EDFT (*Mir* environmental effects payload)
STS-82[b]	February 13, 1997	Smith and Lee	6 hr, 42 min	66 hr, 22 min	Second Hubble Space Telescope servicing. Replace Faint Object Spectrograph (FOS) with Near Infrared Camera and Multi-Object Spectrometer (NICMOS), replace Goddard High Resolution Spectrograph (GHRS) with Space Telescope Imaging Spectrograph (STIS)
	February 14, 1997	Harbaugh and Tanner	7 hr, 27 min		Replace fine guidance sensor, tape recorder, install improve electronics
	February 15, 1997	Smith and Lee	7 hr, 11 min		Replace data interface unit, reaction wheel assembly
	February 16, 1997	Harbaugh and Tanner	6 hr, 34 min		Replace SADE, magnetometer cover, thermal blankets
	February 17, 1997	Smith and Lee	5 hr, 17 min		Install thermal blanket patches

Table 3–50. Space Shuttle Extravehicular Activity (1989–1998[a]) (Continued)

Mission	Date	Astronaut	Individual EVA Time per Astronaut	Cumulative Time in Space	Description
STS-87[c]	November 24, 1997	Scott and Doi	7 hr, 43 min	12 hr, 43 min	Rescue SPARTAN
	December 3, 1997	Scott and Doi	5 hr, 0 min		ISS preparation
STS-88[d]	December 7, 1998	Ross and Newman	7 hr, 21 min	42 hr, 44 min	ISS assembly
	December 8, 1998	Ross and Newman	7 hr, 2 min		
	December 12, 1998	Ross and Newman	6 hr, 59 min		

[a] David S.F. Portree and Robert M. Treviño, *Walking to Olympus: An EVA Chronology*, Monographs in Aerospace History, no. 7 (Washington, DC: National Aeronautics and Space Administration, 1997), pp. 80–126, Available at *http://spaceflight.nasa.gov/spacenews/factsheets/pdfs/EVACron.pdf*; David M. Harland, *The Story of the Space Shuttle*, (London: Springer, 2004), pp. 188–189; *Shuttle Crew Operations Manual*, p. 2-11-1.

[b] "STS-82 Mission Chronology," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-82.htm* (accessed July 5, 2005).

[c] "STS-87 Shuttle Mission Archive," *http://www-pao.ksc.nasa.gov/kscpao/shuttle/missions/sts-87/mission-sts-87.html* (accessed July 5, 2005).

[d] "STS-88 Shuttle Mission Archive," *http://www-pao.ksc.nasa.gov/kscpao/shuttle/missions/sts-88/mission-sts-88.html* (accessed July 5, 2005).

Table 3–51. Space Shuttle Missions Summary (1989–1998)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
28	STS-29/*Discovery*	March 13, 1989 – March 18, 1989	CDR: Michael L. Coats PLT: John E. Blaha MS: James F. Buchli, Robert C. Springer, James P. Bagian	NASA Payload Deployed: Tracking and Data Relay Satellite-D (4)
29	STS-30/*Atlantis*	May 4, 1989 – May 8, 1989	CDR: David M. Walker PLT: Ronald J. Grabe MS: Mark C. Lee, Norman E. Thagard, Mary L. Cleave	NASA Payload Deployed: Magellan
30	STS-28/*Columbia*	August 8, 1989 – August 13, 1989	CDR: Brewster H. Shaw, Jr. PLT: Richard N. Richards MS: James C. Adamson, David C. Leestma, Mark N. Brown	NASA Payload Deployed: None Other Government Payload Deployed: DOD SDS-2 (USA 40)[a] and USA-41[b]
31	STS-34/*Atlantis*	October 18, 1989 – October 23, 1989	CDR: Donald E. Williams PLT: Michael J. McCulley MS: Shannon W. Lucid, Franklin Chang-Diaz, Ellen S. Baker	NASA Payload Deployed: Galileo
32	STS-33/*Discovery*	November 22, 1989 – November 27, 1989	CDR: Frederick D. Gregory PLT: John E. Blaha MS: Manley L. Carter, Jr., F. Story Musgrave, Kathryn C. Thornton	NASA Payload Deployed: None Other Government Payload Deployed: DOD satellite[c]

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
33	STS-32/*Columbia*	January 9, 1990 – January 20, 1990	CDR: Daniel C. Brandenstein PLT: James D. Wetherbee MS: Bonnie J. Dunbar, Marsha S. Ivins, G. David Low	NASA Payload Deployed: None Long Duration Exposure Facility (LDEF) retrieved (was deployed on STS-41-C) Other Government Payload Deployed: DOD SYNCOM IV-5 (LEASAT F5)
34	STS-36/*Atlantis*	February 28, 1990 – March 4, 1990	CDR: John O. Creighton PLT: John H. Casper MS: David C. Hilmers, Richard M. Mullane, Pierre J. Thuot	NASA Payload Deployed: None Other Government Payload Deployed: DOD KH 11-10 (AFP 731)[d]
35	STS-31/*Discovery*	April 24, 1990 – April 28, 1990	CDR: Loren J. Shriver PLT: Charles F. Bolden, Jr. MS: Steven A. Hawley, Kathryn D. Sullivan, Bruce McCandless, II	NASA Payload Deployed: Hubble Space Telescope
36	STS-41/*Discovery*	October 6, 1990 – October 10, 1990	CDR: Richard N. Richards PLT: Robert D. Cabana MS: Bruce E. Melnick, Thomas D. Akers, William M. Shepherd	NASA Payload Deployed: Ulysses
37	STS-38/*Atlantis*	November 15, 1990 – November 20, 1990	CDR: Richard O. Covey PLT: Frank L. Culbertson, Jr. MS: Carle J. Meade, Robert C. Springer, Charles D. Gemar	NASA Payload Deployed: None Other Government Payload Deployed: DOD electronics intelligence satellite USA 67[e]

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
38	STS-35/*Columbia*	December 2, 1990 – December 10, 1990	CDR: Vance D. Brand PLT: Guy S. Gardner MS: John M. Lounge, Jeffrey A. Hoffman, Robert A.R. Parker PS: Ronald A. Parise, Samuel T. Durrance	NASA Payload Deployed: None Carried Astro-1 observatory
39	STS-37/*Atlantis*	April 5, 1991 – April 11, 1991	CDR: Steven R. Nagel PLT: Kenneth D. Cameron MS: Linda M. Godwin, Jerry L. Ross, Jay Apt	NASA Payload Deployed: Gamma Ray Observatory
40	STS-39/*Discovery*	April 28, 1991 – May 6, 1991	CDR: Michael L. Coats PLT: L. Blaine Hammond, Jr. MS: Gregory J. Harbaugh, Donald McMonagle, Guion S. Bluford, Jr., Charles Lacy Veach, Richard J. Hieb	NASA Payload Deployed: None Shuttle Pallet Satellite instrument platform released and retrieved
41	STS-40/*Columbia*	June 5, 1991 – June 14, 1991	CDR: Bryan D. O'Connor PLT: Sidney M. Gutierrez MS: James P. Bagian, Tamara E. Jernigan, Margaret Rhea Seddon PS: F. Drew Gaffney, Millie Hughes-Fulford	NASA Payload Deployed: None Carried SLS-1 using Spacelab pallets with instrument pointing system and igloo

Table 3–51. *Space Shuttle Missions Summary (1989–1998) (Continued)*

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
42	STS-43/*Atlantis*	August 2, 1991 – August 11, 1991	CDR: John E. Blaha PLT: Michael A. Baker MS: Shannon W. Lucid, James C. Adamson, G. David Low	NASA Payload Deployed: Tracking and Data Relay Satellite-5 (TDRS-5)
43	STS-48/*Discovery*	September 12, 1991 – September 18, 1991	CDR: John O. Creighton PLT: Kenneth S. Reightler, Jr. MS: James F. Buchli, Charles D. Gemar, Mark N. Brown	NASA Payload Deployed: Upper Atmosphere Research Satellite (UARS)
44	STS-44/*Atlantis*	November 24, 1991 – December 1, 1991	CDR: Frederick D. Gregory PLT: Terence T. Henricks MS: F. Story Musgrave, Mario Runco, Jr., James S. Voss PS: Thomas J. Hennen	NASA Payload Deployed: None Other Government Payloads Deployed: Defense Support Program satellite DSP F16 (USA 75)[f]
45	STS-42/*Discovery*	January 22, 1992 – January 30, 1992	CDR: Ronald J. Grabe PLT: Stephen S. Oswald MS: Norman E. Th agard, David C. Hilmers, William F. Readdy PS: Roberta L. Bondar, Ulf D. Merbold	NASA Payload Deployed: None Carried International Microgravity Laboratory-1 (IML-1) using Spacelab long module

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
46	STS-45/*Atlantis*	March 24, 1992 – April 2, 1992	CDR: Charles F. Bolden, Jr. PLT: Brian Duffy MS: Kathryn D. Sullivan, David C. Leestma, C. Michael Foale PS: Byron K. Lichtenberg, Dirk D. Frimout	NASA Payload Deployed: None Carried ATLAS-1 on Spacelab pallets
47	STS-49/*Endeavour*	May 7, 1992 – May 16, 1992	CDR: Daniel C. Brandenstein PLT: Kevin P. Chilton MS: Pierre J. Thuot, Kathryn C. Thornton, Richard J. Hieb, Thomas D. Akers, Bruce E. Melnick	NASA Payload Deployed: None Commercial Payload: INTELSAT VI
48	STS-50/*Columbia*	June 25, 1992 – July 9, 1992	CDR: Richard N. Richards PLT; Kenneth D. Bowersox PC: Bonnie J. Dunbar MS: Ellen S. Baker, Carl J. Meade PS: Lawrence J. DeLucas, Eugene H. Trinh	NASA Payload Deployed: None Carried U.S. Microgravity Laboratory-1 (USML-1) Spacelab module
49	STS-46/*Atlantis*	July 31, 1992 – August 8, 1992	CDR: Loren J. Shriver PLT: Andrew M. Allen PC: Jeffrey A. Hoffman MS: Franklin R. Chang-Diaz, Claude Nicollier, Marsha S. Ivins PS: Franco Malerba	NASA-Italian Space Agency Payload: Tethered Satellite System (TSS)-1 ESA Payload: EURECA

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
50	STS-47/*Endeavour*	September 12, 1992– September 20, 1992	CDR: Robert L. Gibson PLT: Curtis L. Brown, Jr. PC: Mark C. Lee MS: Jerome Apt, N. Jan Davis, Mae C. Jemison PS: Mamoru Mohri	NASA Payload Deployed: None Carried Japanese Spacelab-J using Spacelab long module
51	STS-52/*Columbia*	October 22, 1992– November 1, 1992	CDR: James D. Wetherbee PLT: Michael A. Baker MS: Charles Lacy Veach, William M. Shepherd, Tamara E. Jernigan PS: Steven G. MacLean	NASA-Italian Space Agency Deployed Payload: Laser Geodynamic Satellite II (LAGEOS)/Italian Research Interim Stage (IRIS) Carried U.S. Microgravity Payload (USMP-1)
52	STS-53/*Discovery*	December 2, 1992– December 9, 1992	CDR: David M. Walker PLT: Robert D. Cabana MS: Guion S. Bluford, Jr., James S. Voss, Michael R. Clifford	NASA Payload Deployed: None Other Government Payload: DOD SDS-2 (USA 89)[g]
53	STS-54/*Endeavour*	January 13, 1993 – January 19, 1993	CDR: John H. Casper PLT: Donald R. McMonagle MS: Mario Runco, Jr., Gregory J. Harbaugh, Susan J. Helms	NASA Payload Deployed: TDRS-6
54	STS-56/*Discovery*	April 8, 1993 – April 17, 1993	CDR: Kenneth D. Cameron PLT: Stephen S. Oswald MS: C. Michael Foale, Kenneth D. Cockrell, Ellen Ochoa	NASA Payload Deployed and Retrieved: SPARTAN 201 Carried ATLAS-2 Spacelab using Spacelab pallet and igloo

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
55	STS-55/*Columbia*	April 26, 1993 – May 6, 1993	CDR: Steven R. Nagel PLT: Terence T. Henricks MS: Jerry L. Ross, Charles J. Precourt, Bernard A. Harris, Jr. PS: Ulrich Walter, Hans W. Schlegel	NASA Payload Deployed: None Carried German Spacelab D2 using long module
56	STS-57/*Endeavour*	June 21, 1993 – July 1, 1993	CDR: Ronald J. Grabe PLT: Brian Duffy MS: G. David Low, Nancy J. Sherlock (Currie), Peter J.K. Wisoff, Janice E. Voss	NASA Payload Deployed: None Retrieved EURECA; Carried SPACEHAB 01 research module
57	STS-51/*Discovery*	September 12, 1993 – September 22, 1993	CDR: Frank L. Culbertson, Jr. PLT: William F. Readdy MS: James. H. Newman, Daniel W. Bursch, Carl E. Walz	NASA Payload Deployed: Advanced Communications Technology Satellite (ACTS); NASA-German Payload Deployed: Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph-Shuttle Pallet Satellite (ORFEUS-SPAS)
58	STS-58/*Columbia*	October 18, 1993 – November 1, 1993	CDR: John E. Blaha PLT: Richard A. Searfoss MS: Margaret Rhea Seddon, William S. McArthur, Jr., David A. Wolf, Shannon W. Lucid PS: Martin J. Fettman	NASA Payload Deployed: None Carried SLS-2 long module

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
59	STS-61/*Endeavour*	December 2, 1993 – December 13, 1993	CDR: Richard O. Covey PLT: Kenneth D. Bowersox MS: Kathryn C. Thornton, Claude Nicollier, Jeffrey A. Hoffman, F. Story Musgrave, Thomas D. Akers	NASA Payload Retrieved and Redeployed: First Hubble Space Telescope Servicing Mission
60	STS-60/*Discovery*	February 3, 1994 – February 11, 1994	CDR: Charles F. Bolden, Jr. PLT: Kenneth S. Reightler, Jr. MS: N. Jan Davis, Ronald M. Sega, Franklin R. Chang-Diaz, Sergei K. Krikalev	NASA Payload Deployed: Wake Shield Facility (WSF)–attempt to deploy failed; Carried SPACEHAB 02 research module
61	STS-62/*Columbia*	March 4, 1994 – March 18, 1994	CDR: John H. Casper PLT: Andrew M. Allen MS: Pierre J. Thuot, Charles D. Gemar, Marsha S. Ivins	NASA Payload Deployed: None Carried USMP-2 and Office of Aeronautics and Space Technology (OAST)-2
62	STS-59/*Endeavour*	April 9, 1994 – April 20, 1994	CDR: Sidney M. Gutierrez PLT: Kevin P. Chilton MS: Jerome Apt, Michael R. Clifford, Thomas D. Jones PC: Linda M. Godwin	NASA Payload Deployed: None Carried Space Radar Laboratory (SRL-1)
63	STS-65/*Columbia*	July 8, 1994 – July 23, 1994	CDR: Robert D. Cabana PLT: James D. Halsell, Jr. MS: Richard J. Hieb, Carl E. Walz, Leroy Chiao, Donald A. Thomas PS: Chiaki Naito-Mukai	NASA Payload Deployed: None Carried IML-2 Spacelab long module

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
64	STS-64/*Discovery*	September 9, 1994 – September 20, 1994	CDR: Richard N. Richards PLT: L. Blaine Hammond, Jr. MS: Jerry M. Linenger, Susan J. Helms, Carl J. Meade, Mark C. Lee	NASA Payload Deployed and Retrieved: SPARTAN-201 Carried Light Detection and Ranging (LIDAR) in Space Technology Experiment (LITE)
65	STS-68/*Endeavour*	September 30, 1994 – October 11, 1994	CDR: Michael A. Baker PLT: Terrence W. Wilcutt MS: Steven L. Smith, Daniel W. Bursch, Peter J.K. Wisoff PC: Thomas D. Jones	NASA Payload Deployed: None Carried SRL-2
66	STS-66/*Atlantis*	November 3, 1994 – November 14, 1994	CDR: Donald R. McMonagle PLT: Curtis L. Brown, Jr. MS: Joseph R. Tanner, Jean-Francois Clervoy, Scott E. Parazynski PC: Ellen Ochoa	NASA-German Space Agency Payload Deployed and Retrieved: Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere-Shuttle Pallet Satellite (CRISTA-SPAS) Carried ATLAS-3 Spacelab
67	STS-63/*Discovery*	February 3, 1995 – February 11, 1995	CDR: James D. Wetherbee PLT: Eileen M. Collins MS: C. Michael Foale, Janice Voss, Vladimir G. Titov PC: Bernard A. Harris, Jr.	NASA Payload Deployed and Retrieved: SPARTAN-204 Carried SPACEHAB 03 research module

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
68	STS-67/*Endeavour*	March 2, 1995 – March 18, 1995	CDR: Stephen S. Oswald PLT: William G. Gregory MS: John M. Grunsfeld, Wendy B. Lawrence PC: Tamara E. Jernigan PS: Samuel T. Durrance, Ronald A. Parise	NASA Payload Deployed: None Carried Astro-2 on Spacelab module
69	STS-71/*Atlantis*	June 27, 1995 – July 7, 1995	CDR: Robert L. Gibson PLT: Charles J. Precourt MS: Gregory J. Harbaugh, Bonnie J. Dunbar PC: Ellen S. Baker	NASA Payload Deployed: None First Shuttle-*Mir* docking
70	STS-70/*Discovery*	July 13, 1995 – July 22, 1995	CDR: Terence T. Henricks PLT: Kevin R. Kregel MS: Nancy J. Sherlock (Currie), Donald A. Thomas, Mary Ellen Weber	NASA Payload Deployed: TDRS-7
71	STS-69/*Endeavour*	September 7, 1995 – September 18, 1995	CDR: David M. Walker PLT: Kenneth D. Cockrell MS: James H. Newman, Michael L. Gernhardt PC: James S. Voss	NASA Payload Deployed and Retrieved: WSF-2
72	STS-73/*Columbia*	October 20, 1995 – November 5, 1995	CDR: Kenneth D. Bowersox PLT: Kent V. Rominger MS: Catherine G. Coleman, Michael E. Lopez-Alegria PC: Kathryn C. Thornton PS: Fred W. Leslie, Albert Sacco, Jr.	NASA Payload Deployed: None Carried USML-2 Spacelab long module

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Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
73	STS-74/*Atlantis*	November 12, 1995 – November 20, 1995	CDR: Kenneth D. Cameron PLT: James D. Halsell, Jr. MS: Chris A. Hadfield, Jerry L. Ross, William S. McArthur, Jr.	NASA Payload Deployed: None Second Shuttle-*Mir* docking
74	STS-72/*Endeavour*	January 11, 1996 – January 20, 1996	CDR: Brian Duffy PLT: Brent W. Jett, Jr. MS: Leroy Chiao, Winston E. Scott, Koichi Wakata, Daniel T. Barry	NASA Payload Deployed and Retrieved: SPARTAN-OAST Flyer Retrieved Japanese Space Flyer Unit
75	STS-75/*Columbia*	February 22, 1996 – March 9, 1996	CDR: Andrew M. Allen PLT: Scott J. Horowitz MS: Jeffrey A. Hoffman, Maurizio Cheli, Claude Nicollier PC: Franklin R. Chang-Diaz PS: Umberto Guidoni	NASA-Italian Space Agency Payload Deployed: Tethered Satellite System (TSS)-1R Carried USMP-3
76	STS-76/*Atlantis*	March 22, 1996 – March 31, 1996	CDR: Kevin P. Chilton PLT: Richard A. Searfoss MS: Ronald M. Sega, Michael R. Clifford, Linda M. Godwin, Shannon W. Lucid (to *Mir*)	NASA Payload Deployed: None Third Shuttle-*Mir* docking Carried SPACEHAB Single Module
77	STS-77/*Endeavour*	May 19, 1996 – May 29, 1996	CDR: John H. Casper PLT: Curtis L. Brown, Jr. MS: Andrew S.W. Thomas, Daniel W. Bursch, Mario Runco, Jr., Marc Garneau	NASA Payload Deployed and Retrieved: SPARTAN-207 carrying Inflatable Antenna Experiment Carried SPACEHAB research module

Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
78	STS-78/*Columbia*	June 20, 1996 – July 7, 1996	CDR: Terence T. Henricks PLT: Kevin R. Kregel MS: Richard M. Linnehan, Charles E. Brady, Jr. PC: Susan J. Helms PS: Jean-Jacques Favier, Robert Brent Thirsk	NASA Payload Deployed: None Carried Life and Microgravity Spacelab long module
79	STS-79/*Atlantis*	September 16, 1996 – September 26, 1996	CDR: William F. Readdy PLT: Terence W. Wilcutt MS: Jerome Apt, Thomas D. Akers, Carl E. Walz, John E. Blaha (to *Mir*), Shannon W. Lucid (returned from *Mir*)	NASA Payload Deployed: None Fourth Shuttle-*Mir* docking Carried SPACEHAB-05 Double Module
80	STS-80/*Columbia*	November 19, 1996 – December 7, 1996	CDR: Kenneth D. Cockrell PLT: Kent V. Rominger MS: Thomas D. Jones, F. Story Musgrave PC: Tamara E. Jernigan	NASA-German Space Agency Payload Deployed and Retrieved: ORFEUS-SPAS II, Wake Shield Facility-3
81	STS-81/*Atlantis*	January 12, 1997 – January 22, 1997	CDR: Michael A. Baker PLT: Brent W. Jett, Jr. MS: Peter J.K. Wisoff, John M. Grunsfeld, Marsha S. Ivins, Jerry M. Linenger (to *Mir*), John E. Blaha (returned from *Mir*)	NASA Payload Deployed: None Fifth Shuttle-*Mir* docking Carried SPACEHAB Double Module

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Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
82	STS-82/*Discovery*	February 11, 1997 – February 21, 1997	CDR: Kenneth D. Bowersox PLT: Scott J. Horowitz MS: Joseph R. Tanner, Steven A. Hawley, Gregory J. Harbaugh, Steven L. Smith, PC: Mark C. Lee	NASA Payload Retrieved and Redeployed: Second Hubble Space Telescope Servicing Mission
83	STS-83/*Columbia*	April 4, 1997 – April 8, 1997	CDR: James D. Halsell, Jr. PLT: Susan L. Still MS: Michael L. Gernhardt, Donald A. Thomas PC: Janice E. Voss PS: Roger K. Crouch, Gregory T. Linteris	NASA Payload Deployed: None Carried MSL-1 Spacelab long module
84	STS-84/*Atlantis*	May 15, 1997 – May 24, 1997	CDR: Charles J. Precourt PLT: Eileen M. Collins MS: Carlos I. Noriega, Edward Tsang Lu, Elena V. Kondakova, C. Michael Foale (to *Mir*), Jerry M. Linenger (returned from *Mir*) PC: Jean-Francois Clervoy	NASA Payload Deployed: None Sixth Shuttle-*Mir* docking Carried SPACEHAB double module
85	STS-94/*Columbia*	July 1, 1997 – July 17, 1997	CDR: James D. Halsell, Jr. PLT: Susan L. Still MS: Michael L. Gernhardt, Donald A. Thomas PC: Janice E. Voss PS: Roger K. Crouch, Gregory T. Linteris	NASA Payload Deployed: None Carried MSL-1 Spacelab (reflight of STS-83)

Table 3–51. *Space Shuttle Missions Summary (1989–1998) (Continued)*

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
86	STS-85/*Discovery*	August 7, 1997 – August 19, 1997	CDR: Curtis L. Brown, Jr. PLT: Kent V. Rominger. MS: Robert L. Curbeam, Jr., Stephen K. Robinson PC: N. Jan Davis PS: Bjarni V. Tryggvason	Deployed and Retrieved NASA-German Space Agency Payload: CRISTA-SPAS-II
87	STS-86/*Atlantis*	September 25, 1997 – October 6, 1997	CDR: James D. Wetherbee PLT: Michael J. Bloomfield MS: Vladimir G. Titov, Scott E. Parazynski, Jean-Loup J.M. Chretien, Wendy B. Lawrence, David A. Wolf (to Mir), C. Michael Foale (return from *Mir*)	NASA Payload Deployed: None Seventh Shuttle-*Mir* docking Carried SPACEHAB double module
88	STS-87/*Columbia*	November 19, 1997 – December 5, 1997	CDR: Kevin R. Kregel PLT: Steven W. Lindsey MS: Kalpana Chawla, Winston E. Scott, Takao Doi PS: Leonid K. Kadenyuk	NASA Payload Deployed and Retrieved: SPARTAN-201-04 Carried USMP-4
89	STS-89/*Endeavour*	January 22, 1998 – January 31, 1998	CDR: Terrence W. Wilcutt PLT: Joe Frank Edwards, Jr. MS: James F. Reilly, Michael P. Anderson, Salizhan Shakirovich Sharipov, Andrew S.W. Thomas, David A. Wolf PC: Bonnie J. Dunbar	NASA Payload Deployed: None Eighth Shuttle-*Mir* linkup

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Table 3–51. Space Shuttle Missions Summary (1989–1998) (Continued)

Flt No.	Mission/Orbiter	Dates	Crew	Major Payloads
90	STS-90/*Columbia*	April 17, 1998 – May 3, 1998	CDR: Richard A. Searfoss PLT: Scott D. Altman MS: Kathryn P. Hire, Dafydd Rhys Williams PC: Richard M. Linnehan PS: Jay C. Buckey, James A. Pawelczyk	NASA Payload Deployed: None Carried Neurolab Spacelab
91	STS-91/*Discovery*	June 2, 1998 – June 12, 1998	CDR: Charles J. Precourt PLT: Dominic L. Pudwill-Gorie MS: Franklin R. Chang-Diaz, Wendy B. Lawrence, Janet Lynn Kavandi, Valery Victorovitch Ryumin, Andrew Thomas (returned from *Mir*)	NASA Payload Deployed: None Ninth (final) Shuttle-*Mir* docking Carried SPACEHAB double module
92	STS-95/*Discovery*	October 29, 1998 – November 7, 1998	CDR: Curtis L. Brown, Jr. PLT: Steven W. Lindsey MS: Scott E. Parazynski, Pedro Duque PC: Stephen K. Robinson PS: Chiaki Mukai, Sen. John H. Glenn, Jr.	NASA Payload Deployed and Retrieved: SPARTAN-201 Carried SPACEHAB single research module Hubble Space Telescope HOST mission
93	STS-88/*Endeavour*	December 4, 1998 – December 15, 1998	CDR: Robert D. Cabana PLT: Frederick R. Sturckow MS: Jerry L. Ross, Nancy J. Currie, James H. Newman, Sergei K. Krikalev	NASA Payload Deployed: Space Station Unity module First ISS assembly mission

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[a] "USA 40," NSSDC Master Catalog, Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1989-061B* (accessed December 1, 2005). The Federation of American Scientists lists this payload as USA 40 - SDS B1, *http://www.fas.org/spp/military/program/list.htm* (accessed July 6, 2005).

[b] "USA 41," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1989-061C* (accessed December 22, 2005).

[c] No satellite was listed for this Shuttle launch in NSSDC Master Catalog. The Federation of American Scientists lists this payload as USA 48–Magnum 2. Also listed as USA 48–Magnum 2 in the Launch Log of Jonathan's Space Report, *http://planet4589.org/space/log/launchlog.txt* (accessed November 30, 2005).

[d] "KH 11-10," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1990-019B* (accessed November 30, 2005) Listed as USA 53 AFP-731 MISTY in the Launch Log of Jonathan's Space Report.

[e] "USA 67,"*http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1990-097B* (accessed November 30, 2005). Federation of American Scientists lists this payload as USA 67 - SDS B-2. Listed as USA 67 QUASAR 2 in the Launch Log of Jonathan's Space Report.

[f] "USA 75," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-080B* (accessed November 30, 2005). Also listed in the Federation of American Scientists and the Launch Log of Jonathan's Space Report.

[g] "USA 89," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1992-086B* (accessed November 30, 2005). Federation of American Scientists lists this payload as SDS B-3.

Table 3–52. STS-29 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Michael L. Coats PLT: John E. Blaha MS: James F. Buchli, Robert C. Springer, James P. Bagian
Launch	March 13, 1989, 9:57:00 a.m., EST, Kennedy Space Center, Pad 39-B. Launch manifested for February 18 was reassessed for late February/early March launch to replace suspect liquid oxygen turbopumps on *Discovery*'s three main engines and faulty master events controller. Launch on March 13 was delayed 1 hour, 50 minutes due to morning ground fog and upper winds.
Orbital Altitude & Inclination	184 nmi (341 km), 28.45 deg
Launch Weight (lb/kg)	256,357 /116,282
Landing & Postlanding Operations	March 18, 1989, 6:35:51 a.m., PST, Runway 22, Edwards Air Force Base. Orbiter returned to Kennedy Space Center March 24, 1989.
Rollout Distance (ft/m)	9,339/2,847
Rollout Time (seconds)	51
Mission Duration	119 hr, 38 min, 52 sec
Landed Revolution No.	79
Mission Support	Spaceflight Tracking and Data Network (STDN)
Primary Objective	Launch of Tracking and Data Relay Satellite-D
Deployed Satellites	Tracking and Data Relay Satellite-D (TDRS-D/IUS), designated TDRS-4.
Experiments	Orbiter Experiments Autonomous Supporting Instrumentation System (OASIS-I): Recorded environmental data for the Shuttle's primary payloads. It was configured to interface with TDRS-D (4). OASIS-I measured thermal, acoustic, vibration, stress, and acceleration parameters of the satellite during ascent and other phases of the mission.

Table 3–52. STS-29 Mission Characteristics (Continued)

Experiments	Space Station Heat Pipe Advanced Radiator Element (SHARE): SHARE was an attached payload with the TDRS-D/IUS satellite initiated by the Office of Aeronautics and Space Technology (OAST) and managed by the Office of Space Station. The OSSA performed mission implementation and integration. SHARE was a part of NASA's Thermal Energy Management Processes (TEMP) program, supporting the development of various two-phase heat transport systems for use on Space Station *Freedom* or other future space missions. SHARE was designed to test and measure the thermal performance of a single high-capacity heat pipe radiator element in space and to demonstrate whether a natural process could serve as a dependable, durable cooling system for Space Station *Freedom.* Although a faulty manifold design resulted in early termination of the experiment, significant data with respect to the design of spaceborne heat pipes was obtained.
	Air Force Maui Optical System (AMOS) Calibration Test: The tests allowed ground-based electro-optical sensors located on Mt. Haleakala, Maui, Hawaii, to collect imagery and signature data of the orbiter during cooperative overflights. The scientific observations made of the orbiter while performing reaction control system thruster firings, water dumps, or payload bay light activation were used to support the calibration of the AMOS sensors and the validation of spacecraft
	Chromosome and Plant Cell Division in Space Experiment (CHROMEX): Sponsored by the State University of New York at Stony Brook. The CHROMEX was designed to determine whether the roots of a plant developed similarly in microgravity and on Earth. One objective was to test whether the normal rate, frequency, and patterning of cell division in the root tip could be sustained in microgravity. Another objective was to determine whether the fidelity of chromosome partitioning was maintained during and after flight. The CHROMEX used shoots of cell culture-derived daylily (*Hemerocallis* cv. Autumn Blaze) and both tissue cultured and seedling clones of haplopappus (*Haplopappus gracilis*).[a]

Table 3–52. STS-29 Mission Characteristics (Continued)

Experiments	Protein Crystal Growth (PCG): A joint project of NASA's Office of Commercial Programs (OCP) and OSSA, in conjunction with the Center for Macromolecular Crystallography, a NASA OCP-sponsored Center for the Commercial Development of Space (CCDS) at the University of Alabama at Birmingham. Scientific methods and commercial potential were investigated for growing large, high-quality protein crystals in microgravity. Proteins were processed at a "cold" temperature. IMAX Corporation Camera Experiment (IMAX): A 70-mm motion picture camera system photographed Earth with particular emphasis on environmentally threatened areas. Shuttle Student Involvement Project (SSIP) 82-8—Effects of Weightlessness in Spaceflight on the Healing of Bone Fractures: The project was designed to determine if the environmental effects of spaceflight inhibit bone healing. The subjects were four rats with a small piece of bone removed by a veterinarian from a non-weight-bearing bone. A similar group of rats remained on Earth as a control group. The effects of zero gravity on the origin, development, and differentiation of osteoblasts (bone cells) and their production of callus were studied. SSIP 83-9—Chicken Embryo Development in Space: This experiment studied the effects of the space environment on the development of chicken embryos. In the experiment, 32 eggs—16 fertilized two days before launch and 16 fertilized nine days before launch—were placed in an incubator to see if any changes in the developing embryo could be attributed to weightlessness. An identical group of 32 eggs remained on Earth as a control group. On return to Earth, half of each group of eggs were opened and examined to identify any differences in cartilage, bone and digit structures, muscle system, nervous system, facial structure, and internal organs. The second half (16 from spaceflight, 16 from control) were hatched 21 days after fertilization. All embryos fertilized two days before being carried into orbit had died.
Get Away Specials	None
Mission Results	Successful

[a] "CHROMEX-01/STS-29: Life Sciences Objectives," *http://lifesci.arc.nasa.gov/lis2/Chapter4_Programs/CHROMEX/CHROMEX_01.html* (accessed December 1, 2005).

Table 3–53. STS-30 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: David M. Walker PLT: Ronald J. Grabe MS: Mark C. Lee, Norman E. Thagard, Mary L. Cleave
Launch	May 4, 1989, 2:46:59 p.m. EDT, Kennedy Space Center, Pad 39-B. The April 28 launch was scrubbed at T-31 seconds because of a problem with the liquid hydrogen recirculation pump on the No. 1 main engine and a vapor leak in the 4-in (10-cm) liquid hydrogen recirculation line between the orbiter and the external tank. Repairs were made and launch reset for May 4. Liftoff was delayed until the last 5 minutes of a 64-minute window opening at 1:48 a.m. EDT due to cloud cover and high winds at the Kennedy Space Center Shuttle runway, violating return-to-launch-site limits.
Orbital Altitude & Inclination	184 nmi (341 km), 28.85 deg
Launch Weight (lb/kg)	261,118/118,441
Landing & Postlanding Operations	May 8, 1989, 12:43:26 p.m. PDT, Runway 22, Edwards Air Force Base. Orbiter returned to Kennedy Space Center May 15, 1989.
Rollout Distance (ft/m)	10,295/3,138
Rollout Time (seconds)	64
Mission Duration	96 hr, 57 min, 31 sec
Landed Revolution No.	64
Mission Support	STDN
Primary Objective	Launch Magellan
Deployed Satellites	Magellan/IUS
Experiments	FEA: This modular microgravity chemistry/physics laboratory was used to process samples of indium in a float-zone mode. It examined the application of floating zone processes and their effects on crystal quality. The apparatus consisted of a heating element that moved along a track to melt and recrystallize the sample, which was sealed in a Pyrex tube. The super 8-mm camera and computer provided inflight monitoring and data for postflight analysis of each test. MLE: This experiment was used to observe and record the visual characteristics of large-scale lightning as seen from space using the on-board cargo bay TV and 35-mm cameras. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

Table 3–54. STS-28 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Brewster H. Shaw, Jr. PLT: Richard N. Richards MS: James C. Adamson, David C. Leestma, Mark N. Brown
Launch	August 8, 1989, 8:37:00 a.m., EDT, Kennedy Space Center, Pad 39-B. Liftoff occurred during a classified launch window within a launch period extending from 7:30 a.m. to 11:30 a.m., EDT.
Orbital Altitude & Inclination	191 statute mi[a] (166 nmi/307 km), 57 deg
Launch Weight (lb/kg)	Classified
Landing & Postlanding Operations	August 13, 1989, 6:37:08 a.m., PDT, Runway 17, Edwards Air Force Base. Orbiter returned to Kennedy Space Center August 21, 1989.
Rollout Distance (ft/m)	6,015/1,833
Rollout Time (seconds)	46
Mission Duration	121 hr, 0 min, 9 sec
Landed Revolution No.	80
Mission Support	STDN
Primary Objective	DOD mission
Deployed Satellites	SDS 2 (USA 40) and USA 41 military satellites[b]
Experiments[c]	Cosmic Ray Upset Experiment (CRUX)-B Interim Operational Contamination Monitor (IOCM): The OCM was an automatic operation system for the measurement of contamination in the payload bay for the entire mission. The IOCM continuously measured collected particulate and molecular mass at preprogrammed collection surface temperatures. Multi-Purpose Experiment Canister (MPEC): MPEC was a modified GAS canister containing an ejectable, classified U.S. Air Force Space Systems Division experiment. AMOS Calibration Test: See STS-29. Cloud Logic to Optimize Use of Defense Systems (CLOUDS)-1A: This experiment involved photographic sequences of cloud fields to correlate space data and ground data simultaneously and develop functions quantifying the relationship between apparent cloud cover and the viewing angle for various cloud formations. Radiation Monitoring Equipment (RME)–III: This experiment measured ionizing radiation in the orbiter during sequenced time intervals and digitally stored the resulting data.

Table 3–54. STS-28 Mission Characteristics (Continued)

Experiments[d]	Shuttle Activation Monitor (SAM): The SAM measured the amounts of gamma rays in the Shuttle's crew cabin. Visual Function Tester (VFT)-2: This experiment was a biomedical study to determine the effects of microgravity on human visual performance. The experiment examined the vision of crew members exposed to microgravity with regard to contrast thresholds, directional perception, and pattern sensitivities. Aerodynamic Coefficient Identification Package (ACIP): The package instrumentation included triaxial sets of linear accelerometers, angular accelerometers, and angular rate gyros, which sensed the orbiter's motions during flight. ACIP provided the vehicle motion data that was used in conjunction with the Shuttle Entry Air Data System (SEADS) environmental information for determining aerodynamic characteristics below about 300,000 ft altitude.
Get Away Specials[e]	G-0335 Customer: Naval Postgraduate School No information submitted on payload. G-0341 Customer: DOD Space Test Program No information submitted on payload.
Mission Results	Successful
Remarks	DOD mission

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[a] Jenkins, p. 294. Classified mission. No altitude given in NASA sources.

[b] "USA 40," NSSDC Master Catalog, Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1989-061B* (accessed December 1, 2005). The Federation of American Scientists lists this payload as USA 40–SDS B1, *http://www.fas.org/spp/military/program/list.htm* (accessed July 6, 2005); "USA 41," *http://nssdc.gsfc.nasa.gov/database/ScQuery* (accessed December 22, 2005).

[c] Experiments were "acknowledged payloads" by the U.S. Air Force according to Jenkins, p. 296.

[d] Experiments were "acknowledged payloads" by the U.S. Air Force according to Jenkins, p. 296.

[e] *The First 100 GAS Payloads*, NASA Goddard Space Flight Center, Shuttle Small Payloads Project, pp. 108–109.

Table 3–55. STS-34 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Donald E. Williams PLT: Michael J. McCulley MS: Shannon W. Lucid, Franklin Chang-Diaz, Ellen S. Baker
Launch	October 18, 1989, 12:53:40 p.m., EDT, Kennedy Space Center, Pad 39-B. Launch set for October 12 was rescheduled due to a faulty main engine controller on the No. 2 main engine. Launch set for October 17 was rescheduled due to weather constraints for a return-to-launch-site landing at the Kennedy Space Center Shuttle Landing Facility.
Orbital Altitude & Inclination	185 nmi (342 km), 34.3 deg
Launch Weight (lb/kg)	257,569/116,831
Landing & Postlanding Operations	October 23, 1989, 9:33:00 a.m., PDT, Runway 23, Edwards Air Force Base. The orbiter returned to Kennedy Space Center October 29, 1989.
Rollout Distance (ft/m)	9,677/2,950
Rollout Time (seconds)	61
Mission Duration	119 hr, 39 min, 24 sec
Landed Revolution No.	79
Mission Support	STDN
Primary Objective	Launch of Galileo
Deployed Satellites	Galileo/IUS
Experiments	SSBUV Instrument: This experiment compared the observations of several ozone-measuring instruments aboard NOAA satellites and other Earth-monitoring spacecraft being flown. SSBUV data was used to check the calibration of the ozone sounders on these spacecraft to ensure the most accurate readings possible for detecting atmospheric ozone trends and verify the accuracy of the data set of atmospheric ozone and solar irradiance data. The SSBUV used the Space Shuttle's orbital flight path to assess instrument performance by directly comparing data from identical instruments aboard orbiting satellites as the Shuttle and the satellite passed over the same Earth location within a 1-hour window. These orbital coincidences could occur 17 times per day.

Table 3–55. STS-34 Mission Characteristics (Continued)

Experiments	Growth Hormone Concentration and Distribution (GHCD) in Plants: This experiment studied the effects of microgravity on the concentration, turnover properties, and behavior of plant growth hormone (Auxin) in corn shoot tissue. There were four plant canisters: two placed into a gaseous nitrogen freezer, and two were undisturbed. IMAX Cargo-Bay Camera: This 70-mm motion picture camera system photographed Galileo deployment and various Earth features. Student Experiment (SE-82-15)—Zero Gravity Growth of Ice Crystals from Supercooled Water With Relation to Temperature: This student experiment observed the formation of ice crystals at various supercooled temperatures below 0°C (32°F) in a gravity-free environment for high-altitude meteorology and researched the relationships between water vapor saturation and crystal geometry to better understand the absence of gravity. Polymer Morphology (PM-1): This self-contained payload examined the effects of microgravity on the processing of polymers. MLE: See STS-30 Sensor Technology Experiment (STEX): This dosimetry experiment consisted of a self-contained, battery-powered, automated sensor with an internal solid state memory. The STEX Investigated natural background radiation and the radiation from the Radioisotope Thermoelectric Generators (RTG).
Experiments	AMOS: See STS-29
Get Away Specials	None
Mission Results	Successful

Table 3–56. STS-33 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Frederick D. Gregory PLT: John E. Blaha MS: Manley L. Carter, Jr., F. Story Musgrave, Kathryn C. Thornton
Launch	November 22, 1989, 7:23:30 p.m. EST, Kennedy Space Center, Pad 39-B. Launch set for November 20 was rescheduled to allow the changeout of suspect integrated electronics assemblies on the solid rocket boosters.
Orbital Altitude & Inclination	302 nmi (559 km), 28.45 deg
Launch Weight (lb/kg)	Classified
Landing & Postlanding Operations	November 27, 1989, 4:30:16 p.m. PST, Runway 4, Edwards Air Force Base. Orbiter returned to Kennedy Space Center December 4, 1989.
Rollout Distance (ft/m)	7,764/2,366
Rollout Time (seconds)	46
Mission Duration	120 hr, 6 min, 49 sec
Landed Revolution No.	79
Mission Support	STDN
Primary Objective	DOD mission
Deployed Satellites	Classified military satellite[a]
Experiments	AMOS: See STS-29 Auroral Photography Experiment (APE)-B: The APE-B experiment photographed the airglow aurora, auroral optical effects, Shuttle glow phenomenon, and thruster emissions. CLOUDS-I: See STS-28 RME-III: See STS-28 VFT-1: The crew members executed a variety of head movements with eyes both opened and closed, and they reported on sensations of movement. The crew measured the sensory effects accompanying observation of shifting red lights (light-emitting diodes) on a visual target display.
Get Away Specials	Reflight of SD-301, Cosmic Ray Induced Error Rate in Memory Chips (CRUX Cosmic Ray Upset Experiment) Unofficial "classified" GAS.
Mission Results	Successful
Remarks	DOD mission

[a] No satellite listed for this Shuttle launch in NSSDC Master Catalog. The Federation of American Scientists lists this payload as USA 48–Magnum 2. Also listed as USA 48–Magnum 2 in the "Launch Log of Jonathan's Space Report," *http://planet4589.org/space/log/launchlog.txt* (accessed November 30, 2005).

Table 3–57. STS-32 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Daniel C. Brandenstein PLT: James D. Wetherbee MS: Bonnie J. Dunbar, Marsha S. Ivins, G. David Low
Launch	January 9, 1990, 7:35:00 a.m., EST, Kennedy Space Center, Pad 39-A. Launch scheduled for December 18, 1989, was postponed to complete and verify modifications to Pad A, being used for the first time since January 1986. The January 8, 1990, launch was scrubbed due to weather conditions. This was the first use of Mobile Launch Platform for the Shuttle.
Orbital Altitude & Inclination	178 nmi (330 km), 28.5 deg
Launch Weight (lb/kg)	255,994/116,117
Landing & Postlanding Operations	January 20, 1990, 1:35:37 a.m., PST, Runway 22, Edwards Air Force Base. Orbiter returned to Kennedy Space Center January 26, 1990.
Rollout Distance (ft/m)	10,731/3,271
Rollout Time (seconds)	64
Mission Duration	261 hr, 0 min, 37 sec
Landed Revolution No.	171
Mission Support	STDN
Primary Objective	Deployment of SYNCOM IV-F5 and retrieval of LDEF
Deployed Satellites	Defense communications satellite SYNCOM IV-F5 (also known as LEASAT 5)
Experiments	Characterization of Neurospora Circadian Rhythms (CNCR): This experiment, sponsored by NASA's OSSA Life Sciences Division, determined if Neurospora (a pink bread mold) circadian rhythms persisted in microgravity by eliminating most of the exogenously derived environment cues from Earth. The experiment provided data on endogenously-driven biological clocks that could be applied to other organisms. Interim Operational Contamination Monitor (IOCM): See STS-28. PCG: These were a continuing series of approximately 120 different PCG experiments conducted simultaneously using as many as 24 different proteins. See STS-29. FEA: The apparatus was used to conduct the Microgravity Disturbances Experiment. See STS-30. American Flight Echocardiograph (AFE): The AFE obtained data on the inflight cardiovascular dynamics of the space adaptation process to help develop optimal countermeasures to debilitating effects for reasons of personal and operational safety.

Table 3–57. STS-32 Mission Characteristics (Continued)

Experiments	Latitude/Longitude Locator (L3): The crew conducted tests to determine the accuracy and usability of the L3 system in finding the latitude and longitude of known ground sites. Consisted of a modified Hasselblad camera equipped with a wide-angle 40-mm lens, a camera-computer interface developed by Johnson Space Center engineers, and a Graphics Retrieval and Information Display (GRID) 1139 Compass Computer. The crew photographed the same target twice at an interval of approximately 15 seconds and fed information to the GRID computer, which computed two possible locations. The crew, by knowing if the target was north or south of the flight path, could determine which of the two locations was correct and the target's latitude and longitude. MLE: See STS-30. IMAX: This 70-mm motion picture camera system, mounted in the payload bay, was used to photograph various Earth features. AMOS Calibration Test: See STS-29. Shuttle Infrared Leeside Temperature Sensing (SILTS): Mounted on *Columbia*'s vertical tail, SILTS consisted of a cylindrical housing of approximately 20 in (50.8 cm) diameter capped at the leading edge by a hemispherical dome. Mounted inside the dome was an infrared camera that obtained high-resolution infrared imagery of the upper (leeside) surfaces of *Columbia*'s port (left) wing and fuselage during entry. The images provided detailed temperature maps at the surface of the leeside thermal protection materials and indicated the degree of aerodynamic heating of the surface in flight. *Columbia*'s computer activated SILTS at about 400,000 ft (121,920 m) and terminated SILTS after the orbiter passed through the period of significant aerodynamic heating.[a] SEADS: The SEADS nosecap on the *Columbia* contained 14 penetration assemblies, each containing a small hole to sense the nosecap surface air pressure. Measurement of the pressure levels and distribution allowed postflight determination of vehicle attitude and atmospheric density during entry. SEADS operated at an altitude range of 280,000 ft (85,344 m) to landing.[b]
Get Away Specials	None
Mission Results	Successful

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[a] "STS-32 Press Information, December 1989," p. 54, *http://www.jsc.nasa.gov/history/shuttle_pk/mrk/FLIGHT_033-STS-032_MRK.pdf* (accessed December 20, 2005).

[b] "STS-32 Press Information, December 1989," p. 56.

Table 3–58. STS-36 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: John O. Creighton PLT: John H. Casper MS: David C. Hilmers, Richard M. Mullane, Pierre J. Thuot
Launch	February 28, 1990, 2:50:22 a.m., EST, Kennedy Space Center, Pad 39-A. Launch set for February 22 was postponed to February 23, February 24, and February 25 due to the illness of the crew commander and weather conditions. Launch set for February 25 was scrubbed due to malfunction of the range safety computer. Launch set for February 26 was scrubbed due to weather conditions (Note: the external tank was loaded only for launch attempts on February 25, February 26, and launch on February 28). Launch February 28 was set for a classified window lying within a launch period from midnight to 4 a.m. EST.
Orbital Altitude & Inclination	132 nmi (244 km), 62 deg
Launch Weight (lb/kg)	Classified
Landing & Postlanding Operations	March 4, 1990, 10:08:44 a.m., PST, Runway 23, Edwards Air Force Base. Orbiter returned to Kennedy Space Center on March 13, 1990.
Rollout Distance (ft/m)	7,900/2,408
Rollout Time (seconds)	53
Mission Duration	106 hr, 18 min, 23 sec
Landed Revolution No.	72
Mission Support	STDN
Primary Objective	DOD mission
Deployed Satellites	KH-11-10 (AFP-731)[a]
Experiments	RME-III-12: See STS-28. VFT-1: See STS-33. VFT-2: See STS-28.
Get Away Specials	None
Mission Results	Successful
Remarks	DOD mission

[a] "KH 11-10," NSSDC Master Catalog Display: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1990-019B* (accessed November 29, 2005). Listed as "USA 53, AFP-731 MISTY" in the Launch Log of *Jonathan's Space Report*.

Table 3–59. STS-31 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Loren J. Shriver PLT: Charles F. Bolden, Jr. MS: Steven A. Hawley, Kathryn D. Sullivan, Bruce McCandless, II
Launch	April 24, 1990, 8:33:51 a.m. EDT, Kennedy Space Center, Pad 39-B. Launch scheduled for April 18, then April 12, then moved back to April 10 following the Flight Readiness Review. This was the first time that a date set at a Flight Readiness Review was before that shown on previous planning schedules. April 10 launch was scrubbed at T-4 minutes due to a faulty valve in auxiliary power unit (APU) No. 1. The APU was replaced and payload batteries were recharged. The countdown was briefly halted again at T-31 seconds on April 24, because computer software failed to shut down a fuel valve line on ground support equipment. Engineers ordered the valve to shut and countdown continued.
Orbital Altitude & Inclination	330 nmi (611 km) at HST deployment, 28.45 deg
Launch Weight (lb/kg)	249,109/112,994
Landing & Postlanding Operations	April 29, 1990, 6:49:57 a.m. PDT, Runway 22, Edwards Air Force Base. Orbiter returned to Kennedy Space Center on May 7, 1990.
Rollout Distance (ft/m)	8,874/2,705
Rollout Time (seconds)	61
Mission Duration	121 hr, 16 min, 5 sec
Landed Revolution No.	79
Mission Support	STDN
Primary Objective	Deployment of Hubble Space Telescope
Deployed Satellites	Hubble Space Telescope
Experiments	IMAX Cargo Bay Camera (ICBC): The ICBC documented operations outside the crew cabin. The crew used the ICBC to film several Earth observation sites, including the country of Botswana, the San Francisco Bay Area, the Andes Mountains in South America, the Amazon Rainforest, and Japan. IMAX Handheld Camera: The crew used the handheld camera for filming inside the crew cabin.

Table 3–59. STS-31 Mission Characteristics (Continued)

Experiments	Ascent Particle Monitor (APM): An automatic system mounted in the payload bay measured particle contamination or particle detachment during the immediate prelaunch period and during ascent. It consisted of a small box with a fixed door and a moving door mounted in a clamshell arrangement atop an aluminum housing. PCG III: In a continuing series of experiments, the crew modified Vapor Diffusion Apparatus trays to allow for hand seeding of the protein solution droplets. See STS-29. RME-III: See STS-28. Investigations into Polymer Membrane Processing (IPMP): The Batelle organization sponsored this experiment through the Advanced Materials Center for the Commercial Development of Space, partially funded by NASA. The experiment determined porosity control in a microgravity environment. The objective was to flash-evaporate mixed solvent systems in the absence of convection to control the porosity of a polymer membrane. SSIP–Investigation of Arc and Ion Behavior in Microgravity: This experiment studied the effects of weightlessness on electrical arcs and observed the effects of microgravity on an electric arc in a sealed aluminum arc chamber box.[a] AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

[a] Called the Student Science Investigation Project in the STS-31 Press Kit.

Table 3–60. STS-41 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Richard N. Richards PLT: Robert D. Cabana MS: Bruce E. Melnick, Thomas D. Akers, William M. Shepherd
Launch	October 6, 1990, 7:47:15 a.m. EDT, Kennedy Space Center, Pad 39-B. Liftoff occurred 12 minutes after a 2 1/2 hour launch window opened at 7:35 a.m. EDT, October 6; a brief delay was due to weather concerns. An additional 11-second hold occurred at T-5 minutes due to a Ground Launch Sequencer glitch, and at T-31 seconds, the count halted for 22 seconds to correct an orbiter purge, vent, and drain system glitch.
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	259,593/117,749
Landing & Postlanding Operations	October 10, 1990, 6:57:18 a.m. PDT, Runway 22, Edwards Air Force Base. Orbiter returned to Kennedy Space Center October 16, 1990.
Rollout Distance (ft/m)	8,478/2,584
Rollout Time (seconds)	49
Mission Duration	98 hr, 10 min, 3 sec
Landed Revolution No.	65
Mission Support	STDN
Primary Objective	Launch of Ulysses
Deployed Satellites	Ulysses/IUS/PAM-S
Experiments	SSBUV: See STS-34 INTELSAT Solar Array Coupon (ISAC): The ISAC obtained data from the interaction of atomic oxygen with the solar array silver interconnects to assess the condition of the INTELSAT spacecraft stranded in lower Earth orbit (see STS-49). CHROMEX: See STS-29. Voice Command System (VCS): The VCS collected data on voice command recognition accuracy and operated the orbiter's closed-circuit TV system. Solid Surface Combustion Experiment (SSCE): The SSCE studied flame spread in microgravity and improved fire safety aspects of space travel. IPMP: See STS-31.

Table 3–60. STS-41 Mission Characteristics (Continued)

Experiments	PSE: The PSE studied the effects of a proprietary protein molecule on animal physiological systems in microgravity. RME-III: See STS-28. SSIP–Convection in Zero Gravity (SE 81-9): This experiment studied surface tension induced flows in microgravity. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

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Table 3–61. STS-38 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Richard O. Covey PLT: Frank L. Culbertson, Jr. MS: Carle J. Meade, Robert C. Springer, Charles D. Gemar
Launch	November 15, 1990, 6:48:15 p.m. EST, Kennedy Space Center, Pad 39-A. The launch was originally scheduled for July 1990. However, a liquid hydrogen leak found on *Columbia* during the STS-35 countdown prompted three precautionary mini-tanking tests on *Atlantis* at the pad June 29, July 13, and July 25. Tests confirmed a hydrogen fuel leak on the external tank side of the external tank/orbiter 17-in (43.1-cm) quick disconnect umbilical. With a leak that could not be repaired at the pad; *Atlantis* was rolled back to the Vehicle Assembly Building (VAB) August 9, demated, and transferred to the Orbiter Processing Facility (OPF). During the rollback, the vehicle was parked outside the VAB about a day while the *Columbia*/STS-35 stack transferred to the pad for launch. Outside, *Atlantis* suffered minor hail damage to its tiles during a thunderstorm. After repairs were made in the OPF, *Atlantis* transferred to the VAB for mating on October 2. During hoisting operations, a platform beam that should have been removed from the aft compartment fell and caused minor damage that was repaired. The vehicle rolled out to Pad A on October 12. The fourth mini-tanking test was performed October 24 with no excessive hydrogen or oxygen leakage detected. At the Flight Readiness Review, the launch date was set for November 9. The launch was reset for November 15 due to payload problems. Liftoff occurred during a classified launch window lying within a launch period extending from 6:30 p.m. to 10:30 p.m. EST, November 15.
Orbital Altitude & Inclination	142 nmi (262 km), 28.5 deg
Launch Weight (lb/kg)	Classified
Landing & Postlanding Operations	November 20, 1990, 4:42:42 p.m. EST, Runway 33, Kennedy Space Center. Mission was extended one day due to unacceptable crosswinds at the original planned landing site, Edwards Air Force Base. Continued adverse conditions led to a decision to shift landing to Kennedy Space Center. It was the first Kennedy Space Center landing for *Atlantis* and the first end-of-mission landing at Kennedy Space Center since April 1985.
Rollout Distance (ft/m)	9,003/2,744

Table 3–61. STS-38 Mission Characteristics (Continued)

Rollout Time (seconds)	57
Mission Duration	117 hr, 54 min, 22 sec
Landed Revolution No.	78
Mission Support	STDN
Primary Objective	DOD mission
Deployed Satellites	USA 67 electronics intelligence satellite[a]
Experiments	None
Get Away Specials	None
Mission Results	Successful

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[a] "USA 67,"*http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1990-097B* (accessed November 30, 2005). The Federation of American Scientists lists this payload as USA 67–SDS B-2. It is listed as USA 67 QUASAR 2 in the Launch Log of *Jonathan's Space Report*.

Table 3–62. STS-35 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Vance D. Brand PLT: Guy S. Gardner MS: John M. Lounge, Jeffrey A. Hoffman, Robert A.R. Parker PS: Ronald A. Parise, Samuel T. Durrance
Launch	December 2, 1990, 1:49:01 a.m. EST, Kennedy Space Center, Pad 39-B. Launch was first scheduled for May 16, 1990. Following the Flight Readiness Review, the announcement of a firm launch date was delayed to change out a faulty Freon coolant loop proportional valve in the orbiter's coolant system. At a subsequent Flight Readiness Review, the date was set for May 30. Launch on May 30 was scrubbed during tanking due to a minor hydrogen leak in the tail service mast on the mobile launcher platform and a major leak in the external tank/orbiter 17-in (43.1-cm) quick disconnect assembly. Hydrogen also was detected in the orbiter's aft compartment believed associated with a leak involving the 17-in (43.1-cm) umbilical assembly. A mini-tanking test on June 6 confirmed the leak at the 17-in (43.1-cm) umbilical. The umbilical could not be repaired at the pad and the orbiter was returned to the VAB June 12, demated, and transferred to the OPF. Changeout of the orbiter-side 17-in (43.1-cm) umbilical assembly was made with one borrowed from *Endeavour*; the external tank was fitted with new umbilical hardware. The Astro-1 payload was reserviced regularly and remained in *Columbia*'s cargo bay during orbiter repairs and reprocessing.

Table 3–62. STS-35 Mission Characteristics (Continued)

Launch	*Columbia* rolled out to Pad A a second time on August 9 to support a September 1 launch date. Two days before launch, the avionics box on the Broad Band X-Ray Telescope portion of the Astro-1 payload malfunctioned and had to be changed out and retested. Launch was rescheduled for September 6. During tanking, high concentrations of hydrogen were detected in the orbiter's aft compartment, forcing another postponement. NASA managers concluded that *Columbia* had experienced separate hydrogen leaks from the beginning: one of umbilical assembly (now replaced) and one or more in the aft compartment that had resurfaced. Suspicion focused on a package of three hydrogen recirculation pumps in the aft compartment. These were replaced and retested. A damaged Teflon cover seal in the main engine No. 3 hydrogen prevalve was replaced. Launch was rescheduled for September 18. A fuel leak in the aft compartment resurfaced during tanking and the mission was scrubbed again. The STS-35 mission was put on hold until problems were resolved by a special tiger team assigned by the Space Shuttle director. *Columbia* transferred to Pad B October 8, to make room for *Atlantis* on STS-36. Tropical Storm Klaus forced a rollback to the VAB on October 9. The vehicle transferred to Pad B again October 14. A mini-tanking test was conducted on October 30 using special sensors and video cameras and employing a see-through Plexiglas aft compartment door. No excessive hydrogen leakage was detected. Liftoff December 2 was delayed 21 minutes to allow Air Force range time to observe low-level clouds that might impede tracking of Shuttle ascent.
Orbital Altitude & Inclination	190 nmi (252 km), 28.45 deg
Launch Weight (lb/kg)	256,385/116,294
Landing & Postlanding Operations	December 10, 1990, 9:54:08 p.m. PST, Runway 22, Edwards Air Force Base. Mission was cut short one day due to impending bad weather at the primary landing site, Edwards Air Force Base. The orbiter returned to Kennedy Space Center on December 20, 1990.
Rollout Distance (ft/m)	10,450/3,185
Rollout Time (seconds)	58
Mission Duration	215 hr, 5 min, 8 sec
Landed Revolution No.	143
Mission Support	STDN
Primary Objective	Astrophysics observations using Astro-1
Deployed Satellites	None

Table 3–62. STS-35 Mission Characteristics (Continued)

Experiments	Astro-1: An observatory consisting of four telescopes: Hopkins Ultraviolet Telescope (HUT), Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), Ultraviolet Imaging Telescope (UIT), and Broad Band X-Ray Telescope (BBXRT)—all designed for round-the-clock observations of the celestial sphere in the ultraviolet and x-ray ranges.[a] Ultraviolet telescopes were mounted on the Spacelab instrument pointing system carried on pallets in the cargo bay. Loss of both data display units (used for pointing telescopes and operating experiments) during the mission impacted crew-aiming procedures and forced ground teams at Marshall Space Flight Center to aim the ultraviolet telescopes with fine-tuning by the flight crew. • HUT: This telescope studied faint astronomical objects such as quasars, active galactic nuclei, and supernova remnants in the little-explored ultraviolet range below 1200 angstroms. The telescope Observed the outer planets of the solar system to investigate auroras and gained insight into the interaction of each planet's magnetosphere with the solar wind. • WUPPE: This experiment measured the polarization of ultraviolet light from celestial objects such as hot stars, galactic nuclei, and quasars. • UIT: This telescope investigated the present stellar content and history of star formation in galaxies, the nature of spiral structure, and non-thermal sources in galaxies. • BBXRT: This telescope studied various targets, including active galaxies, clusters of galaxies, supernova remnants, and stars. The BBXRT directly measured the amount of energy in electron volts of each x-ray detected. Orbiter Experiments Program (OEX): The OEX was developed to perform flight experiments on a full-scale, lifting vehicle: • SEADS. See STS-32.

Table 3–62. STS-35 Mission Characteristics (Continued)

Experiments	• Shuttle Upper Atmosphere Mass Spectrometer (SUMS): The SUMS complemented SEADS by enabling measurement of atmospheric density above 300,000 ft (91,440 m). The SUMS sampled air through a small hole on the lower surface of the vehicle aft of the nosecap. It used a mass spectrometer operating as a pressure-sensing device to measure atmospheric density in the high altitude and rarefied flow regime where the pressure was too low to use ordinary pressure sensors. The mass spectrometer, incorporated in the SUMS experiment, was spare equipment originally developed for the Viking Mars Lander. • ACIP. See STS-28. • High Resolution Accelerometer Package (HiRAP): This instrument was a three-axis set of highly sensitive accelerometers that measured vehicle motions during the high altitude portion (above 300,000 ft) (91,440 m) of entry. This instrument provided the companion vehicle motion data to be used with the SUMS results. HiRAP had flown on previous missions of the orbiters *Columbia* and *Challenger*. • SILTS: This experiment used a scanning infrared radiometer located atop the vertical tail to collect infrared images of the orbiter's leeside (upper) surfaces during entry, for the purpose of measuring the temperature distribution and the aerodynamic heating environment. On STS-32, the experiment obtained images of the left wing. For STS-35 and STS-40, the experiment was configured to obtain images of the upper fuselage. SILTS had flown on four *Columbia* flights. Shuttle Amateur Radio Experiment-2 (SAREX-2): The SAREX-2 communicated with amateur radio stations within line-of-sight of the orbiter in voice mode or data mode. AMOS Calibration Test: See STS-29. The Shuttle crew conducted a Space Classroom Program called "Assignment–The Stars," to spark student interest in science, math, and technology.

Table 3–62. STS-35 Mission Characteristics (Continued)

Experiments	• Aerothermal Instrumentation Package (AIP): The AIP Comprised about 125 measurements of aerodynamic surface temperature and pressure at discrete locations on the upper surface of the orbiter's left wing, fuselage, and vertical tail. These sensors were originally part of the development flight instrumentation system that flew aboard *Columbia* during its Orbital Flight Test missions (STS-1 through STS-5). They were reactivated through an AIP-unique data handling system. Among other applications, the AIP data provided "ground-truth" information for the SILTS experiment. The AIP had flown on previous *Columbia* flights.
Get Away Specials	None
Mission Results	Marshall and Goddard Space Flight Centers estimated that 70 percent of the planned science data was acquired. Other mission objectives were achieved. The crew experienced trouble dumping waste water due to a clogged drain, they were able to use spare containers.

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[a] See chapter 4, Space Science, of this volume for further discussion of the Astro-1 mission.

Table 3–63. STS-37 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Steven R. Nagel PLT: Kenneth D. Cameron MS: Linda M. Godwin, Jerry L. Ross, Jay Apt
Launch	April 5, 1991, 9:22:44 a.m. EST, Kennedy Space Center, Pad 39-B. Launch set for April 5, 9:18 a.m. was briefly delayed due to low-level clouds in the area.
Orbital Altitude & Inclination	248 nmi (459 km), 28.453 deg
Launch Weight (lb/kg)	255,824/116,040
Landing & Postlanding Operations	April 11, 1991, 6:55:29 a.m. PDT, Runway 33, Edwards Air Force Base. Landing was originally scheduled for April 10 but was delayed one day due to weather conditions at Edwards Air Force Base and Kennedy Space Center.
Rollout Distance (ft/m)	6,364/1,940
Rollout Time (seconds)	56
Mission Duration	143 hr, 32 min, 44 sec
Landed Revolution No.	93
Mission Support	STDN
Primary Objective	Deployment of the Gamma Ray Observatory
Deployed Satellites	Gamma Ray Observatory
Experiments	APM: See STS-31. SAREX II: See STS-35. PCG: A continuing series of experiments, the STS-37 set of PCG experiments used the batch process and flew in a new hardware configuration, the Protein Crystallization Facility, developed by the PCG investigators. See STS-29. Bioserve/Instrumentation Technology Associates Materials Dispersion Apparatus (BIMDA): The BIMDA gathered data by mixing fluids in the microgravity of space. RME-III: See STS-28. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

Table 3–63. STS-37 Mission Characteristics (Continued)

Remarks	Astronauts Ross and Apt performed an unscheduled contingency spacewalk to manually deploy the GRO high-gain antenna. Although the GRO was designed for servicing by the Shuttle, an early mishap with its propulsion system and the later failure of one of its gyroscopes made this impossible. It was brought down in a controlled reentry on June 4, 2000. Crew and Equipment Translation Aids (CETA): Ross and Apt performed a scheduled 6-hour spacewalk to test a method for astronauts to move themselves and equipment while maintaining Space Station *Freedom*.

Table 3–64. STS-39 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Michael L. Coats PLT: L. Blaine Hammond, Jr. MS: Gregory J. Harbaugh, Donald McMonagle, Guion S. Bluford, Jr., Charles Lacy Veach, Richard J. Hieb
Launch	April 28, 1991, 7:33:14 a.m. EDT, Kennedy Space Center, Pad 39-A. The launch was originally scheduled for March 9, but, during processing work at Pad A, significant cracks were found on all four lug hinges on the two external tank umbilical door drive mechanisms. NASA managers opted to roll back the vehicle to the VAB on March 7 and then to the OPF for repair. Hinges were replaced and reinforced with units taken from the orbiter *Columbia. Discovery* returned to the launch pad April 1, and launch was reset for April 23. The mission was again postponed when, during prelaunch external tank loading, a transducer on the high-pressure oxidizer turbopump for main engine No. 3 showed readings out of specification. The transducer and its cable harness were replaced and tested. Launch was rescheduled for April 28.
Orbital Altitude & Inclination	140 nmi (259 km), 57.007 deg
Launch Weight (lb/kg)	247,373
Landing & Postlanding Operations	May 6, 1991, 2:55:35 p.m. EDT, Runway 15, Kennedy Space Center. Landing diverted to Kennedy Space Center because of unacceptably high winds at the planned landing site, Edwards Air Force Base.
Rollout Distance (ft/m)	9,234/2,815
Rollout Time (seconds)	56
Mission Duration	199 hr, 22 min, 22 sec
Landed Revolution No.	133
Mission Support	STDN
Primary Objective	Unclassified DOD mission with multiple payloads
Deployment Satellites	Released and retrieved the SPAS-II

Table 3–64. STS-39 Mission Characteristics (Continued)

Experiments	Air Force Program-675 (AFP-675): AFP-675 was a collection of scientific instruments observing targets such as the atmosphere and the aurora and stars in infrared, far ultraviolet, ultraviolet, and x-ray wavelengths. AFP-675 instruments also analyzed the spectrum of various targets and gases released from or around the Shuttle. Cryogenic Infrared Radiance Instrumentation for Shuttle (CIRRIS): The CIRRUS measured infrared characteristics of atmospheric emissions. Critical Ionization Velocity (CIV): This experiment released four pressure vessels mounted in the payload bay. Each vessel contained a non-hazardous gas. Instruments on SPAS-II observed the resultant gas plume effect. Chemical Release Observation (CRO): The CRO deployed three subsatellites. Each subsatellite released a different chemical. SPAS-II, ground, and airborne scientific instruments observed the resulting cloud. MPEC: See STS-28.[a] RME-III: See STS-28. CLOUDS-I: See STS-28. Space Test Payload-1 (STP-1): This payload consisted of a varied collection of scientific instruments. One instrument observed the luminous "airglow" effect of atomic oxygen on *Discovery*; a second instrument tested a new method of flowing rocket propellants in weightlessness to assist in the design of future engines; and a third instrument observed the fringes of Earth's atmosphere at various times, including sunrise and sunset, in ultraviolet wavelengths.
Get Away Specials	None
Mission Results	Successful
Remarks	Unclassified DOD mission. Work with payloads during the flight involved extensive maneuvering, rendezvous, and proximity operations by *Discovery*.

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[a] The STS-39 Mission Chronology called this experiment the "Multi-Purpose Release Canister." That seems to be an error in that the STS-39 Press Kit and the biography of astronaut Guion Bluford, who released the experiment, called it the "Multi-Purpose Experiment Canister." MPEC also stood for "Multi-Purpose Experiment Canister" in other missions where it was deployed.

Table 3–65. STS-40 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Bryan D. O'Connor PLT: Sidney M. Gutierrez MS: James P. Bagian, Tamara E. Jernigan, Margaret Rhea Seddon PS: F. Drew Gaffney, Millie Hughes-Fulford
Launch	June 5, 1991, 9:24:51 a.m. EDT, Kennedy Space Center, Pad 39-B. Launch was originally set for May 22, 1991. The mission was postponed less than 48 hours before launch when it became known that a leaking liquid hydrogen transducer in the orbiter main propulsion system, which had been removed and replaced during leak testing in 1990, had failed an analysis by the vendor. Engineers feared that one or more of the nine liquid hydrogen and liquid oxygen transducers protruding into fuel and oxidizer lines could break off and be ingested by the engine turbopumps, causing engine failure. In addition, one of the orbiter's five general purpose computers failed completely, along with one of the multiplexer demultiplexers that controlled orbiter hydraulics ordinance and orbiter maneuvering system/ reaction control system functions in the aft compartment. A new general purpose computer and multiplexer demultiplexers were installed and tested. One liquid hydrogen and two liquid oxygen transducers were replaced upstream in the propellant flow system near the 17-in (43.1-cm) disconnect area, which was protected by an internal screen. Three liquid oxygen transducers were replaced at the engine manifold area, while three liquid hydrogen transducers were removed and the openings plugged. The launch was reset for 8 a.m. EDT, June 1, but it was postponed again after several failed attempts to calibrate inertial measurement unit No. 2. The unit was replaced and retested, and launch was rescheduled for June 5.
Orbital Altitude & Inclination	157 nmi (291 km), 39.0156 deg
Launch Weight (lb/kg)	251,970/114,292
Landing & Postlanding Operations	June 14, 1991, 8:39:11 a.m. PDT, Runway 22, Edwards Air Force Base. Orbiter returned to Kennedy Space Center June 21.
Rollout Distance (ft/m)	9,438/2,877
Rollout Time (seconds)	55

Table 3–65. STS-40 Mission Characteristics (Continued)

Mission Duration	218 hr, 14 min, 20 sec
Landed Revolution No.	145
Mission Support	STDN
Primary Objective	SLS-1 mission
Deployed Satellites	None
Experiments	SLS-1 using the Spacelab long module: The tests subjects were humans, 30 rodents, and thousands of jellyfish. The primary SLS-1 experiments studied six body systems. The body systems investigated were: 1) cardiovascular/ cardiopulmonary (heart, lungs and blood vessels); 2) renal/endocrine (kidneys and hormone-secreting organs and glands); 3) blood (blood plasma); 4) immune system (white blood cells); 5) musculoskeletal (muscles and bones); and 6) neurovestibular (brains and nerves, eyes, and inner ear). Of the 18 investigations, 10 involved humans, 7 involved rodents, and 1 used jellyfish. The experiments were: • Influence of Weightlessness Upon Human Autonomic Cardiovascular Controls • In-flight Study of Cardiovascular Deconditioning • Vestibular Experiments in Spacelab • Protein Metabolism During Spaceflight • Fluid-Electrolyte Regulation During Spaceflight • Pulmonary Function During Weightlessness • Lymphocyte Proliferation in Weightlessness • Influence of Spaceflight on Erythrokinetics in Man • Cardiovascular Adaptation to Microgravity • Pathophysiology of Mineral Loss During Spaceflight • Regulation of Erythropoiesis During Spaceflight • Regulation of Blood Volume During Spaceflight • Bone, Calcium, and Spaceflight • A Study of the Effects of Space Travel on Mammalian Gravity Receptors • Effects of Microgravity-Induced Weightlessness on Aurelia Ephyra Differentiation and Statolith Synthesis • Skeletal Myosin Isoenzymes in Rats Exposed to Microgravity • Effects of Microgravity on Biochemical and Metabolic Properties of Skeletal Muscle in Rats • The Effects of Microgravity on the Electron Microscopy, Histochemistry, and Protease Activities of Rat Hind-limb Muscles

Table 3–65. STS-40 Mission Characteristics (Continued)

Experiments	Orbital Acceleration Research Experiment (OARE): This experiment was designed to accurately measure aerodynamic acceleration rates in zero gravity to expand the database of knowledge in predicting orbital drag in the design of future space systems like Space Station *Freedom*. Middeck Zero-Gravity Dynamics Experiment (MODE): This experiment studied the behavior of space structures and contained fluids in microgravity. Scale models of truss beams for large space structures of the future were attached to a vibrating device to analyze the stresses that developed. Fluid slosh forces, in a partially filled container, were measured during vibration. The results yielded insight into developing efficient techniques for fluid transfer in space. OEX: The OEX program provided a mechanism for flight research experiments to be developed and flown aboard a Space Shuttle orbiter. Since the program's inception, 13 experiments were developed for flight. Principal investigators for these experiments represented Langley and Ames Research Centers, Johnson Space Center, and Goddard Space Flight Center. Seven OEX experiments flew on STS-40. Included among this group were six experiments conceived by Langley researchers and one experiment developed by Johnson. • SEADS: See STS-32. • SUMS: See STS-35. Both SEADS and SUMS provided entry atmospheric environmental (density) information. This data, when combined with vehicle motion data, was used to determine in-flight aerodynamic performance characteristics of the orbiter. • ACIP: See STS-28. • HiRAP: See STS-35. • SILTS: This experiment used a scanning infrared radiometer located atop the vertical tail to collect infrared images of the orbiter's leeside (upper) surfaces during entry, for the purpose of measuring the temperature distribution and the aerodynamic heating environment. On STS-32, the experiment obtained images of the left wing. For STS-35 and STS-40, the experiment was configured to obtain images of the upper fuselage. SILTS had flown on four *Columbia* flights. • AIP: See STS-35.

Table 3–65. STS-40 Mission Characteristics (Continued)

Get Away Specials	Twelve GAS canisters were installed on the GAS bridge in the cargo bay for experiments in materials science, plant biology, and cosmic radiation. G-021 Customer: ESA Solid State Microaccelerometer Experiment: This experiment tested a new kind of very sensitive, highly miniaturized accelerometers intended for applications on a number of ESA space missions. G-052 Customer: GTE Laboratories, Inc. Experiment in Crystal Growth: This experiment grew two crystals of gallium arsenide (GaAs). Growth of the two crystals in space was part of a comprehensive research program to systematically investigate the effect of gravity-driven fluid flow on GaA crystal growth. G-091 Customer: CSUN Aerospace Group Orbital Ball Bearing Experiment: A team of researchers from California State University, Northridge (CSUN) built an apparatus called the Orbital Ball Bearing Experiment (OBBEX) to test the effects of melting cylindrical metal pellets in microgravity. If successful, this experiment might produce a new type of ball bearing. G-105 Customer: Alabama Space & Rocket Center In-Space Commercial Processing: Scientists at the University of Alabama in Huntsville (UAH) used five experiments to study possible commercial in-space processing opportunities. Two experiment packages in the canister processed organic films and crystals that might be used in optical communications and computers. A third investigated electroplated metals to study special catalytic or reactive properties, or resistance to corrosion. A fourth experiment studied technology used to refine and process organic materials such as medical samples. The fifth experiment collected cosmic ray interactions on film emulsion while helping scientists assess materials that might be used in future massive cosmic ray detectors to be flown on the Shuttle or Space Station *Freedom* or to determine exposure to energetic particles on Earth. The U.S. Space and Rocket Center provided the sixth experiment which studied the effects of cosmic radiation on the chromosomes and genes of a common yeast.

Table 3–65. STS-40 Mission Characteristics (Continued)

Get Away Specials	G-286 Customer: OMNI International, Ltd., and Duke University Foamed Ultralight Metals: This experiment demonstrated the feasibility of producing, in orbit, foams of ultralight metals for possible application as shock-absorbing panel-backing to improve the shielding of both crewed and uncrewed vehicles and satellites, including Space Station *Freedom*, against hypervelocity impacts either from micrometeroids or orbiting debris. G-405 Customer: Frontiers of Science Foundation Chemical Precipitate Formation: This experiment returned data on the formation of six insoluble inorganic chemical precipitates. The experiment investigated the rate of formation and terminal size of precipitate particles when the growth was unimpaired by settling due to gravity. G-408 Customer: The Mitre Corporation Five Microgravity Experiments: One GAS can contained five student experiments from the Worcester Polytechnic Institute. One attempted to grow large zeolite crystals. Another studied the behavior of fluids in microgravity. A third, the Environmental Data Acquisition System, recorded information about sound, light, temperature, and pressure within the GAS can. The fourth measured Shuttle acceleration along three axes with a high degree of precision. A fifth experiment studied the fogging of film in space. G-451 Customer: Nissho Iwai American Flower and Vegetable Seeds Exposure to Space: Sakana Seeds Corp. in Yokohama, Japan, and the Nissho Iwai American Corp. in New York, New York, jointly sent 19 varieties of flower and vegetable seeds into space to determine how the unknown variables of microgravity affected seed growth. After the Shuttle landed and the seeds were recovered, the companies distributed the seeds to amateur growers.

Table 3–65. STS-40 Mission Characteristics (Continued)

Get Away Specials	G-455 Customer: Nissho Iwai American Semiconductor Crystal Growth Experiment: Investigated the potential advantages of crystal growth under microgravity. There were two experiments: PbSnTe crystal growth from vapor and GaAs crystal growth from metallic solution. This payload was sponsored by Fujitsu Ltd. in Kawasaki, Japan, and Nissho Iwai Corp. in Tokyo, Japan. G-507 Customer: Goddard Space Flight Center Orbiter Stability Experiment: This experiment measured the Space Shuttle's spectrum of small angular motions (or "jitter") produced by the operation of mechanical systems, thruster firings, and human motions during normal crew activity. In addition to the vibration measurements made, Goddard's GAS can also carried a passive experiment to test the effects of radiation on photographic film. G-616 Customer: Thomas Hancock The Effect of Cosmic Radiation on Floppy Disks and Plant Seeds Exposure to Microgravity: This payload consisted of two experiments. The first investigated static computer memory (floppy disks) to determine if cosmically charged particles produced changes in data integrity or structure. The second looked for changes in the physiology or growth of 38 different types of plant seeds. Each cultivator was examined postflight and compared with samples from the same seed lot that remained on Earth for a wide variety of possible effects or changes. Several of the floppy disks contained programs developed by elementary school students. In addition, a large number of plant seeds were distributed to every elementary and junior high school student in the Redlands, California, Unified School District, the sponsor of the experiment. G-486 Sponsor: EDSYN, Inc., Van Nuys, California Six Active Soldering Experiments
Mission Results	Successful
Remarks	This was the first mission dedicated solely to life sciences using the Spacelab habitable module.

Table 3–66. STS-43 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: John E. Blaha PLT: Michael A. Baker MS: Shannon W. Lucid, James C. Adamson, G. David Low
Launch	August 2, 1991, 11:01:59 a.m. EDT, Kennedy Space Center, Pad 39-A. Launch was originally set for July 23, but was moved to July 24 to allow time to replace a faulty integrated electronics assembly that controlled orbiter/external tank separation. The mission was postponed again about 5 hours before liftoff on July 24 due to a faulty main engine controller on the No. 3 main engine. The controller was replaced and retested; launch was reset for August 1. Liftoff set for 11:01 a.m. was delayed and postponed because of a cabin pressure vent valve reading at 12:28 p.m. due to unacceptable weather at the return-to-launch-site location. Launch was reset for August 2.
Orbital Altitude & Inclination	174 nmi (322 km), 28.45 deg
Launch Weight (lb/kg)	259,374/117,650
Landing & Postlanding Operations	August 11, 1991, 8:23:25 a.m. EDT, Runway 15, Kennedy Space Center.
Rollout Distance (ft/m)	9,890/3,014
Rollout Time (seconds)	60
Mission Duration	213 hr, 21 min, 22 sec
Landed Revolution No.	142
Mission Support	STDN
Primary Objective	Deployment of TDRS-E
Deployed Satellites	TDRS-5/IUS
Experiments	SHARE II: This experiment demonstrated microgravity thermal vacuum performance of a heat pipe radiator for heat rejection. SSBUV Instrument: See STS-34. Tank Pressure Control Equipment (TPCE): This experiment determined the effectiveness of jet mixing for controlling tank pressures and equilibrating fluid temperatures. Optical Communications Through Windows (OCTW): This experiment demonstrated the optical transmission of data from the crew cabin to the payload bay. APE-B: See STS-33.

Table 3–66. STS-43 Mission Characteristics (Continued)

Experiments	PCG III: Part of a continuing series of experiments, this mission's experiments were conducted using bovine insulin. See STS-29. BIMDA: See STS-37. IPMP: See STS-31. Space Acceleration Measurement System (SAMS): The SAMS provided acceleration data to characterize the middeck and/or middeck-mounted experiments acceleration environment. SSCE: See STS-41. Ultraviolet Plume Imager (UVPI): No flight hardware; the orbiter was used as a calibration target for space-based ultraviolet sensors. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

Table 3–67. STS-48 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: John O. Creighton PLT: Kenneth S. Reightler, Jr. MS: James F. Buchli, Charles D. Gemar, Mark N. Brown
Launch	September 12, 1991, 7:11:04 p.m. EDT, Kennedy Space Center, Pad 39-A. Launch was delayed 14 minutes by a faulty communication link between Kennedy Space Center and Mission Control in Houston.
Orbital Altitude & Inclination	313 nmi (580 km), 57 deg
Launch Weight (lb/kg)	240,062/108,890
Landing & Postlanding Operations	September 18, 1991, 12:38:42 a.m. PDT, Runway 22, Edwards Air Force Base. Landing was scheduled for Kennedy Space Center but was diverted to Edwards due to bad weather. Orbiter returned to Kennedy Space Center September 26, 1991.
Rollout Distance (ft/m)	9,384/2,860
Rollout Time (seconds)	50
Mission Duration	128 hr, 27 min, 34 sec
Landed Revolution No.	80
Mission Support	STDN
Primary Objective	Deployment of the UARS
Deployed Satellites	UARS
Experiments	APM: See STS-31. MODE: See STS-40. SAM: See STS-28. Cosmic Ray Effects and Activation Monitor (CREAM): The monitor collected data on cosmic ray energy loss spectra, neutron fluxes, and induced radioactivity. The data was obtained from the same locations used to gather data for the SAM experiment in an attempt to correlate data between the two.

Table 3–67. STS-48 Mission Characteristics (Continued)

Experiments	Physiological and Anatomical Rodent Experiment (PARE): First in a series of planned experiments, on physiological and developmental adaptation to microgravity, the PARE-01 experiment examined changes caused by exposure to microgravity in anti-gravity muscles (used for movement) and in tissues not involved in movement. Eight young, healthy rats flew on the Shuttle. After flight, full ground studies housing an identical group of animals under identical conditions (except for the presence of gravity) were conducted. Both groups were housed in self-contained animal enclosure modules that provided food, water, and environmental control throughout the flight. The experiment's design and intent received the review and approval of the animal care and use committees at both NASA and the University of Arizona. Laboratory animal veterinarians oversaw the selection, care, and handling of the rats. Following the flight, the principle investigator thoroughly evaluated the rat tissues. PCG II-2: A continuation of earlier studies, PCG II-2 investigated processes for growing large protein crystals in space. This experiment consisted of 60 vapor diffusion crystal growth chambers. See STS-29. IPMP: See STS-31. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

Table 3–68. STS-44 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Frederick D. Gregory PLT: Terence T. Henricks MS: F. Story Musgrave, Mario Runco, Jr., James S. Voss PS: Thomas J. Hennen
Launch	November 24, 1991, 6:44:00 p.m. EST, Kennedy Space Center, Pad 39-A. Launch set for November 19 was delayed due to a malfunctioning redundant inertial measurement unit on the IUS booster attached to the DSP satellite. The unit was replaced and tested. Launch was reset for November 24 but was delayed for 13 minutes to allow an orbiting spacecraft to pass and to allow external tank liquid oxygen replenishment after minor repairs to the valve in the liquid oxygen replenishment system in the mobile launcher platform.
Orbital Altitude & Inclination	197 nmi (365 km), 28.5 deg
Launch Weight (lb/kg)	259,629/117,766
Landing & Postlanding Operations	December 1, 1991, 2:34:44 p.m. PST, Runway 5, Edwards Air Force Base. Landing was originally scheduled for Kennedy Space Center on December 4, but the 10-day mission was shortened and landing rescheduled following the November 30 on-orbit failure of one of the three orbiter inertial measurement units. Lengthy rollout was due to minimal braking for test.
Rollout Distance (ft/m)	11,191/3,411
Rollout Time (seconds)	107
Mission Duration	166 hr, 50 min, 42 sec
Landed Revolution No.	109
Mission Support	STDN
Primary Objective	Unclassified DOD mission; deployment of DSP satellite
Deployed Satellites	DSP F16/IUS (USA 75)[a]
Experiments	IOCM: See STS-28. Terra Scout: To evaluate the effectiveness of real-time visual observation of terrestrial and oceanic targets, the observational and analytical skills of a photointerpretation specialist were compared with earthbound observation technology of designated targets. Results aided in the development of autonomous sensors.

Table 3–68. STS-44 Mission Characteristics (Continued)

Experiments	Military Man in Space (M88-1): To evaluate the effectiveness of real-time visual observations of terrestrial and oceanic targets, a crew member used optical camera systems to attempt to identify various military-related activities such as ship wakes; truck convoys; armored formations; aircraft operations; dust clouds; and smoke. AMOS Calibration Test: See STS-29. CREAM: See STS-48. SAM: See STS-28. RME-III: See STS-28. VFT-1: See STS-33. Extended Duration Orbiter Medical Project: To investigate countermeasures to orthostatic intolerance problems, this experiment used fluid loading, in which crew members ingested salt tablets and water and used the Lower Body Negative Pressure (LBNP) device. The LBNP created a partial vacuum around the lower body, returning some of the fluids to the legs. UVPI: See STS-43. Bioreactor Flow and Particle Trajectory (BFPT) in Microgravity: This fluid dynamics experiment validated Earth-based predictions for the action of cell cultures in the NASA-developed Slow-Turning Lateral Vessel (STLV) bioreactor. Researchers were interested in the benefits of flying a bioreactor in space because of the expected increased capabilities for cell culturing. The STLV bioreactor, developed as a tool for Space Station *Freedom*, grew cell cultures in a horizontal cylindrical container that slowly rotated, emulating microgravity and keeping the cells continuously suspended while bathing them in nutrients and oxygen. Components from the NASA bioreactor occupied two middeck lockers.
Get Away Specials	None
Mission Results	Successful
Remarks	Unclassified DOD mission Ten-day mission was shortened to seven days because of the on-orbit failure of one of the three orbiter inertial measurement units. Despite the early return, most mission objectives were achieved.[b]

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[a] "USA 75," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-080B* (accessed November 30, 2005). Also listed in the Federation of American Scientists list of military satellites and the Launch Log of *Jonathan's Space Report*.

[b] "STS-44 Mission Summary," Spacelink Cached Web site, *http://spacelink.nasa.gov/NASA.Projects/Human.Exploration.and.Development.of.Space/Human.Space.Flight/Shuttle/Shuttle.Missions/Flight.044.STS-44/Mission.Summary* (cached site accessed December 14, 2005).

Table 3–69. STS-42 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Ronald J. Grabe PLT: Stephen S. Oswald MS: Norman E. Thagard, David C. Hilmers, William F. Readdy PS: Roberta L. Bondar (Canadian Space Agency/CSA), Ulf D. Merbold (ESA)
Launch	January 22, 1992, 9:52:33 a.m. EST, Kennedy Space Center, Pad 39-A. Launch was delayed 1 hour due to weather conditions.
Orbital Altitude & Inclination	163 nmi (302 km), 57 deg
Launch Weight	243,396/110,403
Landing & Postlanding Operations	January 30, 1992, 8:07:17 a.m. PST, Runway 22, Edwards Air Force Base. The mission was extended one day for continued scientific experimentation. Orbiter returned to Kennedy Space Center on February 16, 1992.
Rollout Distance (ft/m)	9,841/3,000
Rollout Time (seconds)	58
Mission Duration	193 hr, 14 min, 44 sec
Landed Revolution No.	128
Mission Support	STDN
Primary Objective	Conduct life sciences research with the IML-1
Deployed Satellites	None
Experiments	IML-1: Working in a pressurized Spacelab long module, the international crew, divided into red and blue teams, conducted experiments on the human nervous system's adaptation to low gravity and the effects of microgravity on other life forms such as shrimp eggs, lentil seedlings, fruit fly eggs, and bacteria. Low gravity materials processing experiments included crystal growth from a variety of substances such as enzymes, mercury iodine, and a virus. IML-1 Life Science Experiments • Biorack – Leukemia Virus Transformed Cells to Microgravity in the Presence of Dimethylsulfoxide (DMSO) – Proliferation and Performance of Hybridoma Cells in Microgravity (HYBRID) – Dynamic Cell Culture System (CULTURE)

Table 3–69. STS-42 Mission Characteristics (Continued)

Experiments	– Chondrogenesis in Micromass Cultures of Mouse Limb Mesenchyme Exposed to Microgravity (CELLS) – Effects of Microgravity and Mechanical Stimulation on the In-Vitro Mineralization and Resorption of Fetal Mouse Bones (BONES) – Why Microgravity Might Interfere With Amphibian Egg Fertilization and the Role of Gravity in Determination of the Dorsal/Ventral Axis in Developing Amphibian Embryos (EGGS) – Effects of Space Environment on the Development of Drosophila Melanogaster (FLY) – Genetic and Molecular Dosimetry of HZE Radiation (RADIAT) – Dosimetric Mapping Inside Biorack (DOSIMTR) – Embryogenesis and Organogenesis of Carausius (MOROSUS) – Gravity-Related Behavior of the Acellular Slime Mold Physarum Polycephalum (SLIME) – Microgravitational Effects on Chromosome Behavior (YEAST) – Growth and Sporulation in Bacillus Subtilis Under Microgravity (SPORES) – Studies on Penetration of Antibiotics in Bacterial Cells in Space Conditions (ANTIBIO) – Transmission of the Gravity Stimulus in Statocyte of the Lentil Root (ROOTS) – Genotype Control of Graviresponse, Cell Polarity, and Morphological Development of Arabidopsis Thaliana in Microgravity (SHOOTS) – Effects of Microgravity Environment on Cell Wall Regeneration, Cell Divisions, Growth and Differentiation of Plants From Protoplasts (PROTO) • Gravitational Plant Physiology Facility Experiments – Gravity Threshold (GTHRES) – Response to Light Stimulation: Phototropic Transients (FOTRAN) • Microgravity Vestibular Investigations • Mental Workload and Performance Experiment • Space Physiology Experiments – Space Adaptation Syndrome Experiments (SASE) – Sled Experiment – Rotation Experiment – Visual Stimulator Experiment – Proprioceptive Experiments – Energy Expenditure in Spaceflight (EES) – Position and Spontaneous Nystagmus (PSN)

Table 3–69. STS-42 Mission Characteristics (Continued)

Experiments	– Measurement of Venous Compliance (MVC) and Evaluation of an Experimental Anti-Gravity Suit – Assessment of Back Pain in Astronauts (BPA) – Phase Partitioning Experiment (PPE) • Biostack (four packages) • Radiation Monitoring Container Device (RMCD) IML-1 Materials Science Experiments • PCG • Cryostat • Single Crystal Growth of Beta-Galactosidase and Beta-Galactosidase/Inhibiter Complex • Crystal Growth of the Electrogenic Membrane Protein Bacteriorhodopsin • Crystallization of Proteins and Viruses in Microgravity by Liquid-Liquid Diffusion – Fluids Experiment System • Study of Solution Crystal Growth in Low Gravity (TGS) • An Optical Study of Grain Formation: Casting and Solidification Technology (CAST) – Vapor Crystal Growth System (VCGS) • Vapor Crystal Growth Studies of Single Mercury Iodide Crystals – Mercury Iodide Crystal Growth (MICG) System • Mercury Iodide Nucleations and Crystal Growth in Vapor Phase • Organic Crystal Growth Facility • Critical Point Facility (CPF) – Study of Density Distribution in a Near-Critical Simple Fluid – Heat and Mass Transport in a Pure Fluid in the Vicinity of a Critical Point – Phase Separation of an Off-Critical Binary Mixture – Critical Fluid Thermal Equilibration Experiment SAMS: See STS-43. SSIP (SE 81-09): Convection in Zero Gravity: This experiment studied surface-tension-induced flows in microgravity. SSIP (SE 83-02): Zero-G Capillary Rise of Liquid Through Granular Porous Media: This experiment studied the flow of liquid through granular porous media. Gelation of SOLS Applied Microgravity Research (GOSAMR): This experiment involved chemical gelation to form precursors for advanced ceramic materials. IPMP: See STS-31. RME-III: See STS-28.

Table 3–69. STS-42 Mission Characteristics (Continued)

Get Away Specials	G-086 Customer: Booker T. Washington Senior High School, Houston, Texas G-086 studied behavioral and physiological effects of microgravity on brine shrimp cysts hatched in space. The experiment also studied thermal conductivity and bubble velocity of air and water in microgravity.
	G-140 Customer: German Space Agency (DARA) G-140 studied the effect that a disturbance of the liquid-liquid interface (due to interfacial tension) had on mass transfer in a liquid-liquid extraction system in a floating zone.
	G-143 Customer: DARA Gas Bubbles in Glass Melts: This experiment researched the process of glass fining, the removal of all visible gaseous inhomogeneities from glass melt.
	G-329 Customer: Swedish Space Corporation G-329 studied solidification phenomena in metal alloys by looking at the dentrite growth in a cadmium-tin alloy.
	G-336 Customer: U.S. Air Force Geophysics Laboratory G-336 measured the visible light reflected by intergalactic dust. Data from those measurements were to be used to validate and update existing data collected in earlier experiments and help provide background measurements of visible light for use in space surveillance.[a]
	G-337 Customer: U.S. Naval Postgraduate School G-337 measured the performance of a thermoacoustic refrigerator under microgravity conditions.
	G-456 Customer: Society of Japanese Aerospace Companies G-456 separated three colored, biologically active enzymes by electrophoresis and compared them to Earth-based patterns.
	G-457 Customer: Society of Japanese Aerospace Companies G-457 cultivated cellular slime mold in microgravity as a preliminary study of a method of gas-liquid separation under conditions of microgravity.

Table 3–69. STS-42 Mission Characteristics (Continued)

Get Away Specials	G-609/G-610 Customer: Australian Space Office Auspace Ltd. designed and built an Australian ultraviolet light telescope for the Australian Space Office. It obtained ultraviolet images of violent events in nearby galaxies. Two interconnected GAS cans housed the payload's components. One contained the optical elements, and the second contained a flight battery and two tape recorders for recording detector data. G-614 Customer: Chinese Society of Astronautics and The American Association for Promotion of Space in China G-614 photographed the motion of simulated debris in the Shuttle under microgravity and remelted various low melting point mixtures of paraffin and Wood's metal while in orbit.
Mission Results	Successful

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[a] *The First 100 GAS Payloads*, (Greenbelt, MD: NASA Goddard Space Flight Center, no date), p. 148.

Table 3–70. STS-45 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Charles F. Bolden, Jr. PLT: Brian Duffy MS: Kathryn D. Sullivan, David C. Leestma, C. Michael Foale PS: Byron K. Lichtenberg, Dirk D. Frimout (ESA)
Launch	March 24, 1992, 8:13:40 a.m. EST, Kennedy Space Center, Pad 39-A. Launch was originally scheduled for March 23, but was delayed one day because of higher than allowable concentrations of liquid hydrogen and liquid oxygen in the orbiter's aft compartment during tanking operations. During troubleshooting, the leaks could not be reproduced, leading engineers to believe they were the result of plumbing in the main propulsion system not thermally conditioned to the super cold propellants. Launch was rescheduled for March 24. Liftoff was delayed about 13 minutes due to low-level clouds at the Kennedy Space Center Shuttle runway.
Orbital Altitude & Inclination	160 nmi (296 km), 57 deg
Launch Weight (lb/kg)	233,650/105,982
Landing & Postlanding Operations	April 2, 1992, 6:23:08 a.m. EST, Runway 33, Kennedy Space Center. Mission extended one day to continue science experiments.
Rollout Distance (ft/m)	9,227/2,812
Rollout Time (seconds)	60
Mission Duration	214 hr, 9 min, 28 sec
Landed Revolution No.	142
Mission Support	STDN
Primary Objective	Atmospheric research using the ATLAS-1
Deployed Satellites	None
Experiments	Atmospheric Laboratory for Applications and Science using the Spacelab pallet and igloo. ATLAS-1 investigations in the areas of atmospheric science, plasma physics, and astrophysics. • Atmospheric Science – Atmospheric Lyman-Alpha Emission (ALAE) – Atmospheric Trace Molecule Spectroscopy (ATMOS) – Grille Spectrometer – Millimeter Wave Atmospheric Sounder (MAS) – Imaging Spectrometric Observatory (ISO)

Table 3–70. STS-45 Mission Characteristics (Continued)

Experiments	• Solar Science – Active Cavity Radiometer Irradiance Monitor (ACRIM) – Measurement of Solar Constant (SOLCON) – Solar Spectrum (SOLSPEC) – Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) – Plasma Physics – Atmospheric Emissions Photometric Imager (AEPI) – Space Experiments with Particle Accelerators (SEPAC) – Energetic Neutral Atom Precipitation (ENAP) • Astrophysics – Far Ultraviolet Space Telescope (FAUST) SSBUV: The instrument is housed in two GAS canisters. See STS-34. Space Tissue Loss (STL): This experiment was a cooperative effort between NASA's OSSA and the Walter Reed Army Institute of Research with hardware sponsored by the U.S. Army Space Test Program and mission management provided by the U.S. Air Force Space Systems Division. The STL experiment studied the effects of the microgravity environment on the biochemistry and functional activity of muscle, bone, and blood cells. Appropriate cell lines were cultured to develop a cellular model for comparison with whole animal results. The muscle atrophy model, consisting of cultured human myocardial cells in a monitored environment, validated skeletal and cardiac muscle atrophy, collected data on catabolic pathways, and tested candidate pharmaceuticals for efficacy in countering tissue loss. IPMP: See STS-31. RME-III: See STS-28. VFT-2: See STS-28. CLOUDS-1A: See STS-28 SAREX II-B: See STS-35.
Get Away Specials	G-229 Customer: GTE Laboratories Experiment in Crystal Growth: This experiment was designed to grow GaAs crystals. GaAs is a versatile electronic material used in high-speed electronics and optoelectronics. The crystal grown on this mission was 1 inch in diameter by 3.5 inches long and was grown using a gradient freeze growth technique.
Mission Results	Successful

Table 3–71. STS-49 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Daniel C. Brandenstein PLT: Kevin P. Chilton MS: Pierre J. Thuot, Kathryn C. Thornton, Richard J. Hieb, Thomas D. Akers, Bruce E. Melnick
Launch	May 7, 1992, 7:40:00 p.m. EDT, Kennedy Space Center, Pad 39-B. Following the Flight Readiness firing of *Endeavour*'s three main engines on April 6, 1992, Shuttle managers decided to replace all three engines due to irregularities detected in two of the high-pressure oxidizer turbopumps; no impact to the launch date was expected. Launch was originally set for May 4 at 8:34 p.m. EDT, but it was moved to May 7 for an earlier launch window opening at 7:06 p.m. EDT to achieve better lighting conditions for photographic documentation of vehicle behavior during the launch phase. Liftoff was delayed 34 minutes due to transoceanic abort landing site weather conditions and a technical glitch with one of the orbiter master events controllers.
Orbital Altitude & Inclination	195 nmi (361 km), 28.34 deg
Launch Weight (lb/kg)	256,597/116,390
Landing & Postlanding Operations	May 16 1992, 1:57:38 p.m. PDT, Runway 22, Edwards Air Force Base. The flight was extended two days to complete mission objectives. The first use of drag chutes during landing, they deployed after nosegear touchdown for data collection only. The orbiter returned to Kennedy Space Center on May 30, 1992.
Rollout Distance (ft/m)	9,490/2,893
Rollout Time (seconds)	58
Mission Duration	213 hr, 17 min, 38 sec
Landed Revolution No.	140
Mission Support	STDN
Primary Objective	Capture, repair, and redeploy INTELSAT VI
Deployed Satellites	INTELSAT VI

Table 3–71. STS-49 Mission Characteristics (Continued)

Experiments	Commercial PCG Experiment: For six years, a variety of hardware configurations were used to conduct PCG experiments aboard 12 Space Shuttle flights. These experiments involved minute quantities of sample materials to be processed. On STS-49, the Protein Crystallization Facility (PCF), developed by the Center for Macromolecular Crystallography (CMC), a NASA Center for the Commercial Development of Space at the University of Alabama-Birmingham, used much larger quantities of materials to grow crystals in batches, using temperature as a means to initiate and control crystallization. The PCF was reconfigured to include cylinders with the same height but varying diameters to obtain different volumes (500 ml, 200 ml, 100 ml, and 20 ml). These cylinders allowed for a relatively minimal temperature gradient and required less protein solution to produce quality crystals. This industry-driven change was brought about by a need to reduce the cost and amount of protein sample needed to grow protein crystals in space, while at the same time increasing the quality and quantity of crystals. The PCF served as the growth chamber for significant quantities of protein crystals. Also flying as part of the CPCG payload complement was a newly designed, state-of-the-art Commercial Refrigerator Incubator Module (CRIM) that allowed for a preprogrammed temperature profile. Developed by Space Industries, Inc., for CMC, the CRIM also provided improved thermal capability and had a microprocessor that used “fuzzy logic” to control and monitor the CRIM’s thermal environment. UVPI Experiment: See STS-43. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

Table 3–71. STS-49 Mission Characteristics (Continued)

Remarks	INTELSAT VI had been stranded in an unusable orbit since its launch aboard a Titan rocket in March 1990. The INTELSAT VI capture required three EVAs. The first spacewalk was on flight day four by Thuot, who was unable to attach a capture bar to INTELSAT from his position on the remote manipulator system arm. A second unscheduled but identical attempt by Thuot failed on the following day. After resting on flight day six, an unprecedented three-person EVA was performed on flight day seven. During the longest EVA so far in U.S. space history (8 hours, 29 minutes), Hieb, Thuot, and Akers grasped the rotating INTELSAT by hand while Brandenstein maneuvered the orbiter, ultimately attaching the capture bar to the satellite and attaching INTELSAT to its new upper stage. The day after capture of the satellite, INTELSAT flight controllers ignited the upper stage to send the satellite to its intended geosynchronous orbit. On flight day eight, Akers and Thornton performed an EVA as part of the Assembly of Station by EVA Methods (ASEM) experiment to demonstrate and verify maintenance and assembly capabilities for Space Station *Freedom*.

Table 3–72. STS-50 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Richard N. Richards PLT: Kenneth D. Bowersox PC: Bonnie J. Dunbar MS: Ellen S. Baker, Carl J. Meade PS: Lawrence J. DeLucas, Eugene H. Trinh
Launch	June 25, 1992, 12:12:23 p.m. EDT, Kennedy Space Center, Pad 39-A. Liftoff was delayed 5 minutes due to weather. This was the first flight of *Columbia* after its scheduled checkout and extensive modification period.
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	257,265/116,693
Landing & Postlanding Operations	July 9, 1992, 7:42:27 a.m. EDT, Runway 33, Kennedy Space Center. Landing was delayed one day due to rain at the primary landing site, Edwards Air Force Base. This was the first landing using new synthetic tread tires.
Rollout Distance (ft/m)	10,674/3,253
Rollout Time (seconds)	59
Mission Duration	331 hr, 30 min, 04 sec
Landed Revolution No.	220
Mission Support	STDN
Primary Objective	Microgravity research using USML-1
Deployed Satellites	None
Experiments	USML-1: A pressurized Spacelab long module with connecting tunnel to the orbiter crew compartment. USML-1 was a national effort to advance microgravity research in a broad array of disciplines. Experiments conducted were: • Crystal Growth Furnace (CGF) • Drop Physics Module (DPM) • Surface Tension Driven Convection Experiment (STDCE) • Zeolite Crystal Growth (ZCG) • PCG • Glovebox Facility (GBX) • SAMS • Generic Bioprocessing Apparatus (GBA) • ASTROCULTURE-1 (ASC) • Extended Duration Orbiter Medical Project (EDOMP) • SSCE

Table 3–72. STS-50 Mission Characteristics (Continued)

Experiments	IPMP: See STS-31. SAREX II: See STS-35. UVPI: See STS-43.
Get Away Specials	None
Mission Results	Successful

Table 3–73. STS-46 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Loren J. Shriver PLT: Andrew M. Allen PC: Jeffrey A. Hoffman MS: Franklin R. Chang-Diaz, Claude Nicollier (ESA), Marsha S. Ivins PS: Franco Malerba (Italian Space Agency Agenzia Spaziale Italiana/ASI)
Launch	July 31, 1992, 9:56:48 a.m. EDT, Kennedy Space Center, Pad 39-A. Liftoff was delayed 48 seconds at L-5 minutes to allow orbiter computers to verify that the orbiter auxiliary power units were ready to start.
Orbital Altitude & Inclination	230 nmi (426 km), 28.45 deg
Launch Weight (lb/kg)	256,031/116,134
Landing & Postlanding Operations	August 8, 1992, 9:11:51 a.m. EDT, Runway 33, Kennedy Space Center. The mission was extended one day to complete scientific objectives.
Rollout Distance (ft/m)	10,860/13,310
Rollout Time (seconds)	66
Mission Duration	191 hr, 15 min, 03 sec
Landed Revolution No.	126
Mission Support	STDN
Primary Objective	Operation and testing of the TSS and deployment of ESA's EURECA
Deployed Satellites	EURECA Joint NASA/Italian Space Agency TSS-1
Experiments	Evaluation of Oxygen Integration with Materials/Thermal Energy Management Processes (EOIM-III/TEMP 2A-3): This experiment gathered accurate data on the reaction rate of atomic oxygen, present in low orbit, on Space Shuttle materials. Collisions with atomic oxygen in orbit cause erosion of many materials. This experiment attempted to identify materials resistant to erosion to be used on future spacecraft.

Table 3–73. STS-46 Mission Characteristics (Continued)

Experiments	Consortium for Materials Development in Space Complex Autonomous Payload (CONCAP II and CONCAP III): This experiment investigated reactions occurring on the surface of materials when exposed to the atomic oxygen flow in Earth orbit on high-temperature, super-conducting films, and on materials degradation/reaction samples. The payloads were flown in 5-ft (1.5-m)-high cylindrical GAS canisters. CONCAP-II studied the changes materials underwent in low-Earth orbit. The payload experiments studied the surface reactions resulting from exposing materials to the atomic oxygen flow experienced by the Space Shuttle in orbit. CONCAP-III measured and recorded absolute accelerations (microgravity levels) in one experiment and electroplated pure nickel metal and recorded the conditions (temperature, voltage, and current) during this process in another experiment. ICBC: The ICBC payload documented operations outside the crew cabin, including prerelease and postrelease of EURECA, TSS-1 flyaway, and TSS reel-out and reel-in. The ICBC also observed Typhoon Janis; the Windward Islands; Java the Sahara desert; Madagascar; Brazil; the Andes mountains; the Tuamoto Archipelago; and the area from Indonesia to Australia. Limited Duration Space Environment Candidate Materials Exposure (LDCE): This experiment evaluated candidate space structure composite materials for degradation due to exposure in low-Earth orbit (passive systems). AMOS: See STS-29. Pituitary Growth Hormone Cell Function (PHCF): This experiment was a study to determine if the exposure of cultured rat pituitary cells to microgravity affected their capacity to produce biologically active growth hormone. UVPI: See STS-43.
Get Away Specials	None
Mission Results	During TSS deployment, the satellite reached a maximum distance of only 840 ft (256 m) from the orbiter instead of the planned 12.5 mi (201 km) because of a jammed tether line. After numerous attempts spanning several days to free the tether, TSS operations were curtailed, and the satellite was stowed for return to Earth. Other mission objectives were accomplished.

Table 3–74. STS-47 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Robert L. Gibson PLT: Curtis L. Brown, Jr. PC: Mark C. Lee MS: Jerome Apt, N. Jan Davis, Mae C. Jemison PS: Mamoru Mohri (Japanese Aerospace Exploration Agency/JAXA)
Launch	September 12, 1992, 10:23:00 a.m. EDT, Kennedy Space Center, Pad 39-B. This launch was the first on-time Shuttle launch since STS-61-B in November 1985.
Orbital Altitude & Inclination	166 nmi (307 km), 57.00 deg
Launch Weight (lb/kg)	258,679/117,335
Landing & Postlanding Operations	September 20, 1992, 8:53:23 a.m. EDT, Runway 33, Kennedy Space Center. The mission was extended one day for further scientific experimentation. This mission was the first time the drag chute was deployed in operational mode, before nosegear touchdown. Postlanding assessment showed that the orbiter veered off the runway centerline, possibly due to the drag chute.
Rollout Distance (ft/m)	8,567/2,611
Rollout Time (seconds)	51
Mission Duration	190 hr, 31 min, 11 sec
Landed Revolution No.	125
Mission Support	STDN
Primary Objective	Materials and life sciences research using Spacelab-J
Deployed Satellites	None

Table 3–74. STS-47 Mission Characteristics (Continued)

Experiments	Spacelab-J: A joint NASA-National Space Development Agency of Japan (NASDA) mission using a Spacelab long module. The international crew was divided into red and blue teams for round-the-clock operations. Spacelab-J included materials science and life sciences experiments, of which NASDA sponsored 37 and NASA sponsored 8. Materials science investigations covered such fields as biotechnology; electronic materials; fluid dynamics and transport phenomena; glasses and ceramics; metals and alloys; and acceleration measurements. Life sciences investigations covered human health; cell separation and biology; development biology; animal and human physiology and behavior; space radiation; and biological rhythms. Test subjects included crew members; Japanese koi fish; cultured animal and plant cells; chicken embryos; fruit flies; fungi and plant seeds; and frogs and frog eggs. Sponsored by NASA • Materials Science – SAMS – Inflight Demonstration of the Space Station *Freedom* Health Maintenance Facility Fluid Therapy System • Life Science – PCG – Monitoring Astronauts' Functional State – Autogenic Responses to Microgravity – Bone Cell Research – Amphibian Development in Microgravity: The STS-47 Frog Embryology Experiment – Lower Body Negative Pressure Countermeasure Against Orthostatic Intolerance After Space Flight – Plant Cell Research Experiment on Spacelab J: Mitotic Disturbances in Daylily (Hemerocallis) Somatic Embryos After an 8-Day Spaceflight – Magnetic Resonance Imaging After Exposure to Microgravity From the National Space Development Agency of Japan • Materials Science – Growth Experiments of Narrow Band-Gap Semiconductor Pb-Sn-Te Single Crystal in Space – Growth of Pb-Sn-Te Single Crystal by Traveling Zone Method – Growth of Semiconductor Compound Single Crystal InSb by Floating Zone Method

Table 3–74. STS-47 Mission Characteristics (Continued)

Experiments	– Casting of Superconducting Composite Materials – Formation Mechanism of Deoxidation Products in Iron Ingot Deoxidized With Two or Three Elements – Preparation of Particle Dispersion–Alloys – Diffusion in Liquid State and Solidification of Binary System – High-Temperature Behavior of Glass – Growth of Silicon Spherical Crystals and Surface Oxidation – Study of Solidification of Immiscible Alloy – Fabrication of Ultra-Low-Density, High-Stiffness Carbon Fiber/Aluminum Composites – Study on Liquid Phase Sintering – Fabrication of Si-As-Te: Semiconductor in Microgravity Environment – Gas Evaporation in Low Gravity – Drop Dynamics in an Acoustic Resonant Chamber and Interference with the Acoustic Field – Bubble Behavior in Thermal Gradient and Stationery Acoustic Wave – Preparation of Optical Materials Used in Non-Visible Region – Marangoni Effort-Induced Convection in Material Processing Under Microgravity – Solidification of Eutectic System Alloys in Space – Growth of Samarskite Crystal in Microgravity – Crystal-Growth Experiment on Organic Metals in Low Gravity – Crystal Growth of Compound Semiconductors in a Low-Gravity Environment • Life Science – Endocrine and Metabolic Changes in Payload Specialist – Neurophysiological Study of Visuo-Vestibular Control of Posture and Movement in Fish During Adaptation to Weightlessness – Comparative Measurement of Visual Stability in Earth and Cosmic Space – Crystal Growth of Enzymes in Low Gravity – Studies on the Effects of Microgravity on the Ultrastructure and Functions of Cultured Mammalian Cells – Effect of Low Gravity on Calcium Metabolism and Bone Formation in Chick Embryo – Separation of Biogenic Materials by Electrophoresis Under Zero Gravity – Genetic Effects of HZE and Cosmic Radiation

Table 3–74. STS-47 Mission Characteristics (Continued)

- Manual Control in Space Research on Perceptual Motor Functions Under Microgravity Condition
- Study on the Biological Effect of Cosmic Radiation and the Development of Radiation Protection Technology
- Circadian Rhythm of Conidiation in Neurospora Crassa
- Electrophoretic Separation of Cellular Materials Under Microgravity
- Study of the Effects of Microgravity on Cell Growth of Human Antibody-Producing Cells and Their Secretions
- Organ Differentiation from Cultured Plant Cells Under Microgravity
- Health Monitoring of Japanese Payload Specialist
- Autonomic Nervous and Cardiovascular Responses Under Reduced Gravity

Israeli Space Agency Investigation About Hornets (ISAIAH): This experiment attempted to gain greater insight into the ability of hornets to construct a comb in the direction of the gravitational vector by observing their comb-building in microgravity. It also investigated the effects of microgravity on comb integrity, social interactions, hornet venom toxicity, and the semiconductive properties of hornet cuticle.

SSCE: See STS-41.

SAREX II: See STS-35.

AMOS Calibration Test: See STS-29.

UVPI: See STS-43.

Table 3–74. STS-47 Mission Characteristics (Continued)

Get Away Specials	G-102 Customer: TRW Defense and Space Systems Group and Explorer Scouts POSTAR: Consisted of seven experiments: 1. Capillary Pumping Experiment: This experiment investigated pumping liquids using capillary feed tubes. 2. Cosmic Ray Experiment: This experiment studied the direction and composition of cosmic rays. 3. Crystal Growth Experiment: This experiment examined high-quality, lattice-structure crystals using nickel sulfate. 4. Emulsions Experiment: This experiment investigated the formation of oil/water emulsions. 5. Fluid Droplet Experiment: This experiment studied the shape of fluid droplets in microgravity. 6. Floppy Disk Experiment: This experiment investigated the effect of low-level radiation on floppy disks. 7. Fiber Optics Experiment: This experiment examined the degradation of fiber optic cables under the space radiation environment.
	G-255 Customer: University of Kansas Scientific studies contained four experiments: Composite Materials: This experiment compared composites manufactured in microgravity with those made on Earth. Cell Membrane: This experiment investigated the formation of biological membranes in microgravity. Crystal Growth: This experiment studied the effects of microgravity on bond angles and the structure of crystals. Space Seeds: This experiment studied the effects of the space environment on germination rates and health of seeds.
	G-300 Customer: Matra Marconi Space Thermal Conductivity of Liquids in Microgravity: This experiment measured the thermal conductivity of liquids in microgravity. It was the first GAS payload from France.
	G-330 Customer: Swedish Space Corporation Material Science Experiments: Crystal Growth and Electromigration: These experiments investigated the breakdown of a solid/liquid interface.

Table 3–74. STS-47 Mission Characteristics (Continued)

Get Away Specials	G-482 Customer: Space Aerospace, Ltd., Quebec, Canada Baking Bread in Space: This experiment investigated the behavior of bread yeast in the absence of gravity and in the presence of normal atmospheric pressure. G-520 Customer: The Independent Television News of England Scientific Experiments for Educational Competition: Consisted of two experiments: Chemical Gardens Experiment: This experiment deposited cobalt nitrate crystals into a container of sodium silicate solution. The ensuing crystal growth was compared to crystals grown on Earth. The Liesegang Rings Experiment: This experiment deposited a silver nitrate solution on a compound containing potassium chromate. Silver nitrate diffused through potassium chromate and formed a precipitate in the shape of rings. The investigation attempted to produce rings on a large scale to aid in determining why they were produced. This was the first British school experiment to fly in space. G-521 Customer: Canadian Space Agency QUESTS: This experiment involved performing directional solidification and diffusion experiments in microgravity using 3 gradient furnaces and 12 isothermal furnaces. G-534 Customer: NASA Headquarters Pool Boiling Experiment: This experiment investigated the effects of heat flux and liquid subcooling on nucleate pool boiling in a long-term, reduced-gravity environment. G-613 Customer: University of Washington Liquid Droplet Rotating-Collector Experiment: This was a proof-of-concept experiment testing the ability of a centrifugal collector to recover a free fluid stream in microgravity.
Mission Results	Successful

Table 3–75. STS-52 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: James D. Wetherbee PLT: Michael A. Baker MS: Charles Lacy Veach, William M. Shepherd, Tamara E. Jernigan PS: Steven G. MacLean (CSA)
Launch	October 22, 1992, 1:09:39 p.m. EDT, Kennedy Space Center, Pad 39-B. The targeted launch date in mid-October slipped when managers decided to replace the No. 3 engine, prompted by concerns about possible cracks in the liquid hydrogen coolant manifold on the engine nozzle. Liftoff set for 11:16 a.m. was delayed about 2 hours due to crosswinds at the Kennedy Space Center landing strip, violating return-to-launch-site criteria, and clouds at the Banjul transoceanic abort landing site.
Orbital Altitude & Inclination	163 nmi (302 km), 28.45 deg
Launch Weight (lb/kg)	250,130/113,457
Landing & Postlanding Operations	November 1, 1992, 9:05:52 a.m. EST, Runway 33, Kennedy Space Center. The drag chute was again deployed before nosegear touchdown to allow further study of deployment dynamics.
Rollout Distance (ft/m)	10,708/3,263
Rollout Time (seconds)	63
Mission Duration	236 hr, 56 min, 13 sec
Landed Revolution No.	158
Mission Support	STDN
Primary Objective	Deploy LAGEOS II and operation of USMP-1
Deployed Satellites	LAGEOS II/IRIS

Table 3–75. STS-52 Mission Characteristics (Continued)

Experiments	USMP-1: The payload included three experiments mounted on two connected Multipurpose Experiment Support Structures mounted in the cargo bay. The USMP-1 experiments were: • Lambda Point Experiment (LPE): This experiment studied fluid behavior in microgravity. • French-sponsored *Material Pour l'Etude Des Phenomenes Interessant La Solidification Sur Terre Et En Orbite* (Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit) (MEPHISTO): This experiment studied metallurgical processes in microgravity. • SAMS: This was a study of the microgravity environment on board the Space Shuttle. Canadian Experiments-2 (CANEX-2): These experiments were a complement of space technology, space science, materials processing, and life sciences experiments located in both the cargo bay and middeck, including: • Space Vision System (SVS) • Materials Exposure in Low-Earth Orbit (MELEO) • Queen's University Experiment in Liquid-Metal Diffusion (QUELD) • Phase Partitioning in Liquids (PARLIQ) • Sun Orbiter Glow-2 (OGLOW-2) • Space Adaptation Tests and Observations (SATO) • Sun Photo Spectrometer Earth Atmosphere Measurement (SPEAM-2) • Vestibular-Ocular Reflex Check • Body Water Changes in Microgravity • Assessment of Back Pain in Astronauts • Illusions During Movement Altitude Sensor Package (ASP): The ASP featured three ESA independent sensors mounted on a Hitchhiker plate in the cargo bay: • Modular Star Sensor • Yaw Earth Sensor and Low Altitude Conical Earth Sensor • Tank Pressure Control Experiment/Thermal Phenomena Commercial Materials Dispersion Apparatus Instrument Technology Associates Experiments (CMIX): These experiments were designed to mix a variety of sample fluids/solids in microgravity and bioprocessing modules designed to mix fluids to perform immune cell response in microgravity.

Table 3–75. STS-52 Mission Characteristics (Continued)

Experiments	CPCG: See STS-49. Crystal Vapor Transport Experiment (CVTE): The CVTE consisted of two furnaces, which provided a controlled environment for growth of selected materials. • Heat Pipe Performance Experiment (HPP): The HPP experiment developed the understanding of heat pipe behavior in microgravity. PSE-02: The PSE-02 determined the effects of a proprietary protein molecule on an animal's physiological system. Shuttle Plume Impingement Experiment (SPIE): The SPIE consisted of sensing hardware mounted on the remote manipulating system to measure the atomic oxygen flux and contamination. Tank Pressure Control Experiment/Thermal Phenomena (TPCE/TP): This experiment determined the effectiveness of jet mixing as a means of controlling tank pressures and equilibrating fluid temperatures, contained in a GAS canister.
Get Away Specials	None
Mission Results	Successful

Table 3–76. STS-53 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: David M. Walker PLT: Robert D. Cabana MS: Guion S. Bluford, Jr., James S. Voss, Michael R. Clifford
Launch	December 2, 1992, 8:24:00 a.m. EST, Kennedy Space Center, Pad 39-A. Liftoff was originally set for 6:59 a.m. but was delayed to allow sunlight to melt ice on the external tank that had formed after tanking due to overnight temperatures in the upper 40s°F and light wind.
Orbital Altitude & Inclination	174 nmi (322 km), 57.00 deg
Launch Weight (lb/kg)	243,952/110,655
Landing & Postlanding Operations	December 9, 1992, 12:43:47 p.m. PST, Runway 22, Edwards Air Force Base. Landing was originally set for Kennedy Space Center but was diverted due to clouds in the landing strip vicinity. The drag chute was deployed before nosegear touchdown. After landing, a small leak was detected in a forward thruster that delayed crew egress before a fan and winds dissipated the leaking gas. The orbiter returned to Kennedy Space Center on December 18, 1992.
Rollout Distance (ft/m)	10,165/3,098
Rollout Time (seconds)	73
Mission Duration	175 hr, 19 min, 47 sec
Landed Revolution No.	115
Mission Support	STDN
Primary Objective	Deploy a classified DOD payload
Deployed Satellites	SDS-2 (USA 89)

Table 3–76. STS-53 Mission Characteristics (Continued)

Experiments	Glow Experiment (GLO)/Cryogenic Heat Pipe Experiment (CRYOHP) Payload (GCP): These payloads were contained in or attached to GAS hardware. The GLO experiment observed orbiter and air glow, primary reaction control system and vernier reaction control system burns, water dumps, and flash evaporator system operations. The CRYOHP experiment measured the performance of liquid oxygen heat pipes in microgravity. Battlefield Laser Acquisition Sensor Test (BLAST): This test evaluated the use of a spaceborne laser receiver to detect laser energy and provide laser communication uplink for GPS information from specific ground sites. CLOUDS: See STS-28. CREAM: See STS-48. Fluid Acquisition and Resupply Experiment (FARE): The FARE investigated the fill, refill, and expulsion of fluid tanks and liquid motion in microgravity. Handheld, Earth-oriented, Real-time, Cooperative, User-friendly, Location-Targeting and Environmental System (HERCULES): The HERCULES performed geolocating operations over selected ground sites. Microcapsules in Space-1 (MIS-1): This experiment demonstrated the capability to produce microencapsulated ampicillin in microgravity to compare with Earth-produced ampicillin. RME-III: See STS-28. STL: See STS-45. VFT-2: See STS-28. Orbital Debris Radar Calibration System (ODERACS): This system qas to release six calibration spheres from *Discovery.* The spheres—two with diameters of 6 in (15-cm), two with 4-in (10-cm) diameters, and two with 2-in (5-cm) diameters—were to be placed in a 175-nmi (377-km) orbit when they were ejected from the Shuttle's cargo bay. The primary objective of the experiment was to provide a source for fine-tuning of the Haystack Radar, located in Tyngsboro, Massachusetts, and operated by the Lincoln Laboratory at the Massachusetts Institute of Technology for the U.S. Air Force.
Get Away Specials	None
Mission Results	The ODERACS was not deployed. After attempts to communicate with the experiment without response, it was determined that a battery had been drained before launch. Other mission objectives were successfully met.
Remarks	This was the final Shuttle flight for the DOD.

Table 3–77. STS-54 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: John H. Casper PLT: Donald R. McMonagle MS: Mario Runco, Jr., Gregory J. Harbaugh, Susan J. Helms
Launch	January 13, 1993, 8:59:30 a.m. EST, Kennedy Space Center, Pad 39-B. Liftoff was delayed about 7 minutes due to concerns associated with upper atmospheric winds.
Orbital Altitude & Inclination	165 nmi (306 km), 29.45 deg
Launch Weight (lb/kg)	259,764[a]/117,827
Landing & Postlanding Operations	January 19, 1993, 8:37:49 a.m. EST, Runway 33, Kennedy Space Center. Landing was delayed one orbit due to ground fog at Kennedy Space Center.
Rollout Distance (ft/m)	8,724/2,659
Rollout Time (seconds)	49
Mission Duration	143 hr, 38 min, 19 sec
Landed Revolution No.	95
Mission Support	STDN
Primary Objective	Deploy TDRS-6
Deployed Satellites	TDRS-6/IUS
Experiments	Diffuse X-ray Spectrometer (DXS): The DXS was a Hitchhiker experiment sponsored by Goddard Space Flight Center. Data was collected on x-ray radiation from diffuse sources in deep space. The DXS determined the wavelength and intensity of the strongest x-ray lines emitted by the hot stellar gases released by supernovas.[b] Commercial General Bioprocessing Apparatus (CGBA): The CGBA performed two functions, biological sample processing and stowage. The Generic Bioprocessing Apparatus (GBA) module was a self-contained mixing and incubation module for samples. Temperature-controlled stowage was achieved in the CRIM. CHROMEX: See STS-29. PARE-02: See STS-48. SAMS: See STS-43. SSCE: See STS-41.
Get Away Specials	None
Mission Results	Successful

[a] Jenkins, p. 302.

[b] See chapter 4, Space Science, for further discussion of the Diffuse X-ray Spectrometer experiment.

Table 3–78. STS-56 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Kenneth D. Cameron PLT: Stephen S. Oswald MS: C. Michael Foale, Kenneth D. Cockrell, Ellen Ochoa
Launch	April 8, 1993, 1:29:00 a.m. EDT, Kennedy Space Center, Pad 39-B. The first launch attempt on April 6 was halted at T-11 seconds by orbiter computers when instrumentation on the liquid hydrogen high point bleed valve in the main propulsion system indicated "off" instead of "on." Later analysis indicated that the valve was properly configured; 48-hour scrub turnaround procedures were implemented. The final countdown on April 8 proceeded smoothly.
Orbital Altitude & Inclination	160 nmi (296 km), 57.00 deg
Launch Weight (lb/kg)	236,659/107,347
Landing & Postlanding Operations	April 17, 1993, 7:37:19 a.m. EDT, Runway 33, Kennedy Space Center. Landing, originally set for April 16, at Kennedy Space Center was waved off due to weather. A second reefing line was added to drag chute for greater stability.
Rollout Distance (ft/m)	9,530/2,905
Rollout Time (seconds)	62
Mission Duration	222 hr, 8 min, 24 sec
Landed Revolution No.	147
Mission Support	STDN
Primary Objective	ATLAS-2
Deployed Satellites	SPARTAN-201: Retrieved April 13[a]
Experiments	ATLAS-2: This mission used Spacelab pallet and igloo to collect data on the relationship between the Sun's energy output and Earth's middle atmosphere and their affect on the ozone layer. The atmospheric instruments were: • ATMOS experiment • MAS • SSBUV/A spectrometer: See STS-34. The solar science instruments were: • SOLSPEC instrument • SUSIM • Active Cavity Radiometer (ACR) • SOLCON experiments SAREX II: See STS-35.

Table 3–78. STS-56 Mission Characteristics (Continued)

Experiments	Commercial Materials Dispersion Apparatus Instrumentation Technology Associates Experiment (CMIX): This collection of experiments was housed in a CRIM, replacing a middeck locker. The CRIM contained four MDA mini-lab units designed to mix a variety of fluids and/or fluids and solids in the microgravity environment. The CRIM also contained 10 Bioprocessing Modules (BPM) designed to mix fluids to perform immune cell response experiments in microgravity. The experiments studied protein crystal growth, collagen polymerization, fibrin clot formation, liquid-solid diffusion, and the formation of thin film membranes. See STS-52. Experiments developed by the University of Alabama Huntsville Consortium for Materials Development in Space and its affiliates included: • Bone Cell Differentiation (MDA) • Immune Cell Response (MDA) • Diatoms (MDA) • Mouse Bone Marrow Cells (MDA) • Nerve/Muscle Cell Interactions • Phagocytosis (MDA) • Other experiments evaluating fluids mixing, invertebrate and bone development, virus sub-unit assembly and collagen self-assembly, and formation of drug encapsulated liposomes • Live Cell Investigations (BPM) Experiments developed by ITA, Inc. and its affiliates include: • Collagen Reconstitution (MDA) • Microencapsulation (MDA) • Urokinase Protein Crystal Growth (MDA) • Bacterial Aldolase and Rabbit Muscle Aldolase Protein Crystal Growth (MDA) • HIV Reverse Transcriptase (MDA) • RNA Protein Crystal Growth (MDA) • Methylase Protein Crystal Growth (MDA) • Lysozyme Protein Crystal Growth (MDA) • DNA-Heme Protein Crystal Growth (MDA) • Brine Shrimp Development (MDA) • Cell Research (MDA) • Other commercial MDA experiments included inorganic assembly (proprietary), myoglobin protein crystal growth, dye and yeast cell diffusion, and engineering tests • Mustard Seed Germination (MDA-student)

Table 3–78. STS-56 Mission Characteristics (Continued)

Experiments	PARE-03: See STS-48.
	STL-3: See STS-53.
	CREAM: See STS-48.
	HERCULES: See STS-53.
	RME-III: See STS-28.
	AMOS Calibration Test: See STS-29.
Get Away Specials	Solar Ultraviolet Experiment (SUVE) Customer: Colorado Space Grant Consortium Measured extreme ultraviolet and far ultraviolet solar irradiance with two spectrometers.
Mission Results	Successful

[a] See chapter 4, Space Science, for details of the SPARTAN satellites.

Table 3–79. STS-55 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Steven R. Nagel PLT: Terence T. Henricks MS: Jerry L. Ross, Charles J. Precourt, Bernard A. Harris, Jr. PS: Ulrich Walter (Germany), Hans W. Schlegel[a] (Germany)
Launch	April 26, 1993, 10:50:00 a.m. EDT, Kennedy Space Center, Pad 39-A. Launch first set for February slipped to early March after questions arose about turbine blade tip seal retainers in the high-pressure oxidizer turbopumps on the orbiter main engines. When engineers could not verify whether old or new retainers were on *Columbia*, NASA opted to replace all three turbopumps at the pad as a precaution. The March 14 launch date slipped again after a hydraulic flex hose burst in the aft compartment during a Flight Readiness Test. All 12 hydraulic lines in the aft compartment were removed and inspected; 9 lines were reinstalled, and 3 new lines were put in. Launch set for March 21 was pushed back 24 hours due to range conflicts caused by a Delta II one-day launch delay. Orbiter computers aborted a liftoff attempt on March 22 at T-3 seconds because of incomplete ignition of the No. 3 main engine. The liquid oxygen preburner check valve leaked internally, causing an overpressurized purge system that, in turn, prevented full engine ignition. This was the first on-the-pad main engine abort since return to flight, and the third in program history (51-F and 41-D were the other two). The valve leak was later traced to contamination during manufacturing. NASA decided to replace all three main engines on *Columbia* with spares. Launch was reset for April 24 but was scrubbed early on launch morning when one of orbiter's three inertial measurement units (IMU) gave a possible faulty reading. Liftoff was postponed for 48 hours to allow removal and replacement of the IMU. The final launch countdown on April 26 proceeded smoothly.
Orbital Altitude & Inclination	163 nmi (302 km), 28.45 deg
Launch Weight (lb/kg)	255,441[b]/115,866
Landing & Postlanding Operations	May 6, 1993, 7:29:59 a.m. PDT, Runway 22, Edwards Air Force Base. Landing originally set for Kennedy Space Center moved to Edwards because of cloud cover.

Table 3–79. STS-55 Mission Characteristics (Continued)

Rollout Distance (ft/m)	10,125/3,086
Rollout Time (seconds)	61
Mission Duration	239 hr, 39 min, 59 sec
Landed Revolution No.	159
Mission Support	STDN
Primary Objective	Microgravity research using the German Spacelab D-2
Deployed Satellites	None
Experiments	Spacelab D-2: The D-2 mission augmented the German microgravity research program started by the D-1 Spacelab mission in 1985. The German Aerospace Research Establishment (DLR) had been tasked by the DARA to conduct the second mission. DLR, NASA, ESA, and agencies in France and Japan contributed to D-2's scientific program. Eleven nations participated in the experiments. Of the 88 experiments conducted on the D-2 mission, four were NASA-sponsored. The crew worked in two shifts around-the-clock to complete investigations in the areas of fluid physics; materials sciences; life sciences; biological sciences; technology; Earth observations; atmospheric physics; and astronomy. The payloads were: Material Science Experiment Double Rack for Experiment Modules and Apparatus (MEDEA) • Floating Zone Growth of GaAs • Floating Zone Crystal Growth of Gallium-Doped Germanium • Hysteresis of the Specific Heat CV During Heating and Cooling Through the Critical Point • Diffusion of Nickel in Liquid Copper-Aluminum and Copper-Gold Alloys • Directional Solidification of Ge/GaAs Eutectic Composites • Cellular-Dendritic Solidification with Quenching of Aluminum-Lithium Alloys • Thermoconvection at Dendritic-Eutectic Solidification of an Al-Si Alloy • Growth of GaAs from Gallium Solutions Werkstofflabor (WL) Material Sciences Laboratory • OSIRIS: Oxide Dispersion Strengthened Single Crystalline Alloys Improved by Resolidification in Space • Impurity Transport and Diffusion in InSb Melt Under Microgravity Environment • Cellular-Dendritic Solidification at Low Rate of Aluminum-Lithium Alloys • Directional Solidification of the LiF-LiBaF3-Eutectic • Separation Behavior of Monotectic Alloys

Table 3–79. STS-55 Mission Characteristics (Continued)

Experiments	• Liquid Columns' Resonances • Stability of Long Liquid Columns • Higher Modes and Their Instabilities of Oscillating Marangoni Convection in a Large Cylindrical Liquid Column • Marangoni-Benard Instability • Onset of Oscillatory Marangoni Flows • Marangoni Convection in a Rectangular Cavity • Stationary Interdiffusion in a Non-Isothermal Molten Salt Mixture • Transport Kinetics and Structure of Metallic Melts • Nucleation and Phase Selection During Solidification of Undercooled Alloys • Heating and Remelting of an Allotropic Fe-C-Si Alloy in a Ceramic Skin and the Effect of the Volume Change on the Mold's Stability • Immiscible Liquid Metal Systems • Convective Effects on the Growth of GaInSb Crystals • Vapor Growth of InP-Crystal with Halogen Transport in a Closed Ampoule • Solution Growth of GaAs Crystals Under Microgravity • Crystallization of Nucleic Acids and Nucleic Acid-Protein Complexes • Crystallization of Ribosomal Particles Holographic Optics Laboratory (HOLOP) • Marangoni Convection in a Rectangular Cavity • Interferometric Determination of the Differential Interdiffusion Coefficient of Binary Molten Salts • IDILE: Measurements of Diffusion Coefficients in Aqueous Solution • NUGRO: Phase Separation in Liquid Mixtures with Miscibility Gap Baroreflex (BA) • Residual Acceleration in Spacelab D2 • Transfer Function Experiment • Robotics Experiment (ROTEX) • Anthrorack (AR) • Cardiovascular Regulation at Microgravity • Central Venous Pressure During Microgravity • Leg Fluid Distribution at Rest and Under Lower Body Negative Pressure • Determination of Segmental Fluid Content and Perfusion • Left Ventricular Function at Rest and Under Stimulation • Peripheral and Central Hemodynamic Adaptation to Microgravity During Rest, Exercise, and Lower Body Negative Pressure in Humans

Table 3–79. STS-55 Mission Characteristics (Continued)

Experiments	• Tonometry–Intraocular Pressure in Microgravity • Tissue Thickness and Tissue Compliance Along Body Axis Under Microgravity Conditions • Changes in the Rate of Whole-Body Nitrogen Turnover, Protein Synthesis, and Protein Breakdown Under Conditions of Microgravity • Regulation of Volume Homeostasis in Reduced Gravity Possible Involvement of Atrial Natriuretic Factor Urodilatin and Cyclic GMP • Effects of Microgravity on Glucose Tolerance • Effects of Spaceflight on Pituitary-Gonad-Adrenal Function in the Human • Adaptation to Microgravity and Readaptation to Terrestrial Conditions • Pulmonary Perfusion and Ventilation in Microgravity Rest and Exercise • Ventilation Distribution in Microgravity • Effects of Microgravity on the Dynamics of Gas Exchange, Ventilation, and Heart Rate in Submaximal Dynamic Exercise • Cardiovascular Regulation in Microgravity • Biolabor (BB) • Development of Vestibulocular Reflexes in Amphibia and Fishes with Microgravity Experience • Comparative Investigations of Microgravity Effects on Structural Development and Function of the Gravity-Perceiving Organ of Two Water-Living Vertebrates • Structure and Function-Related Neuronal Plasticity of the Central Nervous System of Aquatic Vertebrates During Early Ontogenetic Development Under Microgravity Conditions • Immunoelectron Microscopic Investigation of Cerebellar Development at Microgravity • Gravisensitivity of Cress Roots • Influence of Gravity on Fruiting Body Development of Fungi • Significance of Gravity and Calcium Ions on the Production of Secondary Metabolites in Cell Suspensions • Influence of Conditions in Low-Earth Orbit on Expression and Stability of Genetic Information in Bacteria • Productivity of Bacteria • Fluctuation Test on Bacterial Cultures • Connective Tissue Biosynthesis in Space: Gravity Effects on Collagen Synthesis and Cell Proliferation of Cultured Mesenchymal Cells • Antigen-Specific Activation of Regulatory T-Lymphocytes to Lymphokine Production • Growth of Lymphocytes Under Microgravity Conditions

Table 3–79. STS-55 Mission Characteristics (Continued)

Experiments	• Enhanced Hybridoma Production Under Microgravity • Culture and Electrofusion of Plant Cell Protoplasts Under Microgravity: Morphological/Biochemical Characterization • Yeast Experiment HB-L29/Yeast: Investigations on Metabolism Cosmic Radiation Experiments • Biological Hze-Particle Dosimetry with Biostack • Personal Dosimetry: Measurement of the Astronaut's Ionizing Radiation Exposure • Measurement of the Radiation Environment Inside Spacelab at Locations Which Differ in Shielding Against Cosmic Radiation • Chromosome Aberration • Biological Response to Extraterrestrial Solar UV Radiation and Space Vacuum User Support Structure Payloads • Module Optoelectronic Multispectral Stereo Scanner (MOMS) • Galactic Ultrawide-Angle Schmidt System (GAUSS) • Atomic Oxygen Exposure Tray (AOET) • Material Science Autonomous Payload (MAUS) – Reaction Kinetics in Glass Melts Payload (RKGM) – Pool Boiling – Gas Bubbles in Glass Melts Crew Telesupport Experiment (CTE): Combined an on-board computer-based multimedia documentation file with a real-time, graphical communication between the on-orbit crew members and the ground station. SAREX II: See STS-35.
Get Away Specials	None
Mission Results	Successful
Remarks	Spacelab D-2 conducted the first telerobotic capture of a free-floating object by flight controllers in Germany. The crew conducted the first intravenous saline solution injection in space as part of an experiment to study the human body's response to direct fluid replacement as a countermeasure for amounts lost during spaceflight. The crew also successfully completed an in-flight maintenance procedure for collection of orbiter wastewater that allowed the mission to continue. Spacelabs D1 and D2 were the only Spacelab missions to date with payload operations controlled from a foreign country.

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[a] Integrated into ESA's single European astronaut corp in 1998.

[b] Jenkins, p. 302.

Table 3–80. STS-57 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Ronald J. Grabe PLT: Brian Duffy MS: G. David Low, Nancy J. Sherlock (Currie), Peter J.K. Wisoff, Janice E. Voss
Launch	June 21, 1993, 9:07:22 a.m. EDT, Kennedy Space Center, Pad 39-B. The launch originally targeted for mid-May was rescheduled to June to allow both liftoff and landing to occur in daylight. Liftoff set for June 3 slipped when managers decided to replace the high-pressure oxidizer turbopump on main engine No. 2 after concerns arose over a misplaced inspection stamp on a spring in the pump. Additional time also allowed investigation of an inexplicable loud noise heard after the Shuttle arrived at the launch pad, which was eventually attributed to the ball strut tie-rod assembly inside the 17-in (43-cm) liquid hydrogen line. The launch attempt on June 20 was scrubbed at T-5 minutes due to low clouds and rain at the return-to-launch site at Kennedy Space Center, and weather concerns at all three transoceanic abort landing sites. The launch countdown was the longest since return to flight to allow servicing of payloads at the pad.
Orbital Altitude & Inclination	252 nmi (467 km), 28.45 deg
Launch Weight (lb/kg)	252,710[a]/114,627
Landing & Postlanding Operations	July 1, 1993, 8:52:16 a.m. EDT, Runway 33, Kennedy Space Center. Landing attempts on June 29 and June 30 were waved off due to unacceptable cloud cover and rain showers at Kennedy Space Center. After landing, the STS-57 crew on *Endeavour* talked with the STS-51 crew on *Discovery* at Pad 39-B. It was the first orbiter-to-orbiter crew conversation since the orbiting STS-51-D crew talked with the STS 51-B crew at Kennedy Space Center in 1985.
Rollout Distance (ft/m)	9,954/3,034
Rollout Time (seconds)	65
Mission Duration	239 hr, 44, min, 54 sec
Landed Revolution No.	154
Mission Support	STDN
Primary Objective	Retrieval of EURECA and biomedical and materials science experimentation using the SPACEHAB module
Deployed Satellites	None

Table 3–80. STS-57 Mission Characteristics (Continued)

Experiments	SPACEHAB 01 Experiments: • Commercial Material Science Experiments – Equipment for Controlled Liquid Phase Sintering Experiment-SPACEHAB (ECLiPSE) – GPPM – IPMP – Liquid Encapsulated Melt Zone (LEMZ) – Support of Crystal Growth (SCG) – Zeolite Crystal Growth (ZCG) • Commercial Life Science Experiments – ASTROCULTURE™ – BioServe Pilot Laboratory (BPL) – CGBA – Organic Separation (ORSEP) – PCG – Vapor Diffusion Apparatus and Crystallization Facility Experiments – Direct-Control Protein Crystal Growth – PSE • Johnson Space Center Experiments – Application-Specific Pre-programmed Experiment Culture (ASPEC) – Charged Particle Directional Spectrometer (CPDS) – Human Factors Assessment (HFA) – Neutral Body Posture (NBP) – Tools and Diagnostics System (TDS) • Space Station Experiment – Environmental Control Life Support System (ECLSS) Flight Experiment • Supporting Hardware Overview – Three-Dimensional Microgravity Accelerometer (3-DMA) – SAMS FARE: See STS-53. SAREX-II: See STS-35. AMOS Calibration Test: See STS-29. Consortium for Materials Development in Space Complex Autonomous Payload IV (CONCAP IV): This complex was designed to grow non-linear optical organic thin films and crystals through the physical vapor transport process. The payload was carried on the GAS Bridge Assembly. Superfluid Helium On-Orbit Transfer (SHOOT): SHOOT was designed to develop and demonstrate the technology required to resupply liquid helium containers in space. It was carried on the GAS Bridge Assembly.

Table 3–80. STS-57 Mission Characteristics (Continued)

Get Away Specials	G-022 Customer: ESA, European Space Research and Technology Centre, Noordwijk, the Netherlands Liquid Gauging Technology Experiment: This experiment demonstrated two on-orbit methods of gauging liquids in tanks.
	G-324 Customer: Charleston County School District, Charleston, South Carolina CAN-DO (GEOCAM): The CAN-DO consisted of four 35-mm cameras for Earth photography to compare with Skylab photographs. The canister also contained 350 small passive student experiments that allowed students to participate directly in research by testing the effect of space on various materials.
	G-399 Customer: Dr. Ronald S. Nelson, Inc., Fresno, California Insulin/Artemia/Ion Experiments: These experiments studied Ferritin-tagged insulin, Artemia growth, and salt ion transport across a permeable membrane.
	G-450 Customer: American Institute of Aeronautics and Astronautics, Vandenberg Air Force Base, California Multiple Experiments: G-450 was a multidisciplinary package of six self-contained modules, each containing multiple experiments designed and developed by California elementary, middle, and high school students.
	G-452 Customer: Society of Japanese Aerospace Companies, Tokyo, Japan Crystal Growth of Gallium Arsenide: G-452 had twelve small electric furnaces used to carry out the following experiments in low gravity. Growth of a single gallium-arsenide crystal from the liquid phase. Growth of a gallium-arsenide-based mixed crystal. Addition of a heavy element to gallium-arsenide. Addition of a heavy element to indium-antimony crystal.
	G-453 Customer: Society of Japanese Aerospace Companies, Tokyo, Japan Semiconductor/Superconductor Boiling Experiments: G-453 consisted of three experiments on semiconductors and a superconductor and one experiment on boiling an organic solvent under weightlessness.

Table 3–80. STS-57 Mission Characteristics (Continued)

Get Away Specials	G-454 Customer: Society of Japanese Aerospace Companies, Tokyo, Japan Crystal Growth: This experiment studied the crystal growth of indium-gallium-arsenic from vapor phase under weightlessness, the crystal growth of 3-selenic-niobium from vapor phase, the crystal growth of an optoelectric crystal by the diffusion method, and the formation of superferromagnetic alloy. G-535 Customer: NASA Headquarters, OSSA Pool Boiling Experiment: This was a study of heating vapor and bubble growth/collapse. G-601 Customer: San Diego Section, American Institute of Aeronautics and Astronautics, San Diego, California High Frequency Variations of the Sun: This experiment measured and analyzed high-frequency solar output to better determine the physics of the Sun and other stars. G-647 Customer: Canadian Space Agency, Ottawa, Ontario, Canada Liquid Phase Electroepitaxy, Configurable Hardware for Multidisciplinary Projects in Space (CHAMPS): G-647 provided a versatile payload for materials science experiments in space. The experiment examined a recently developed technique for crystal growth called Liquid Phase Electro-Epitaxy (LPEE) in a microgravity environment. GAS Ballast Payload Customer: Goddard Space Flight Center, Greenbelt, Maryland Ballast payloads were flown for stability when a GAS payload was dropped and no replacement was available. A small accelerometer package recorded accelerations during the mission. Sample Return Experiment: This experiment sat on top of the ballast GAS cans. It quantified extraterrestrial particles and other orbital debris present in the orbiter bay.
Mission Results	Successful

[a] Jenkins, p. 302.

Table 3–81. STS-51 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Frank L. Culbertson, Jr. PLT: William F. Readdy MS: James H. Newman, Daniel W. Bursch, Carl E. Walz
Launch	September 12, 1993, 7:45:00 a.m. EDT, Kennedy Space Center, Pad 39-B. The first launch attempt on July 17 was scrubbed during a hold at T-20 minutes due to premature and unexplained charging of pyrotechnic initiator controllers (PIC), located on the mobile launcher platform (MLP), for T-0 liquid hydrogen vent arm umbilical and solid rocket booster hold-down bolts. The problem was traced to a faulty circuit card in the PIC rack on the MLP. An abbreviated countdown began July 23. A second liftoff attempt on July 24 was halted at T-19 seconds due to a problem with the auxiliary power unit (APU) turbine assembly for one of the two hydraulic power units on the right solid rocket booster. The APU was removed and replaced at pad. Launch was rescheduled for August 4 to August 12 because of concerns relating to the Perseid meteor shower, which was expected to peak on August 11. A liftoff attempt on August 12 was halted at the T-3-second mark due to a faulty sensor monitoring fuel flow on main engine No. 2. This was the fourth pad abort in Shuttle program history that led to a changeout of all three main engines at the pad. The launch was rescheduled for September 10 but then slipped to September 12 to allow time to complete a review of the ACTS design, production, and testing history following the loss of contact with the Mars Observer and NOAA-13 satellite. The countdown proceeded smoothly to an on-time liftoff on September 12.
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	261,486[a]/118,608

Table 3–81. STS-51 Mission Characteristics (Continued)

Landing & Postlanding Operations	September 22, 1993, 3:56:11 a.m. EDT, Runway 15, Kennedy Space Center. A September 21 landing opportunity was waved off due to the possibility of rain within 30 miles of the Shuttle Landing Facility. It was the first end-of-mission night landing at Kennedy Space Center for the Shuttle program.
Rollout Distance (ft/m)	8,271/2,521
Rollout Time (seconds)	50
Mission Duration	236 hr, 11 min, 11 sec
Landed Revolution No.	156
Mission Support	STDN
Primary Objective	Deploy ACTS; deployment and retrieval of ORFEUS-SPAS
Deployed Satellites	ACTS/TOS ORFEUS-SPAS (See chapter 4, Space Science, for a description of science objectives and payload.)
Experiments	IMAX: The ORFEUS-SPAS payload was recorded from the Shuttle using a handheld IMAX camera; the Shuttle was recorded using the Remote IMAX Camera System (RICS) mounted on the free-flying ORFEUS-SPAS.[b] CPCG: See STS-49. CHROMEX: See STS-29. High Resolution Shuttle Glow Spectroscopy (HRSGS-A): This payload obtained high-resolution spectra in the visible and near visible wavelength range of the Shuttle surface glow. APE-B: See STS-33. RME-III: See STS-28. IPMP: See STS-31. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

[a] Jenkins, p. 302.

[b] See chapter 4, Space Science, of this volume for further discussion of the ORFEUS-SPAS mission.

Table 3–82. STS-58 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: John E. Blaha PLT: Richard A. Searfoss MS: Margaret Rhea Seddon, William S. McArthur, Jr., David A. Wolf, Shannon W. Lucid PS: Martin J. Fettman
Launch	October 18, 1993, 10:53:10 a.m. EDT, Kennedy Space Center, Pad 39-B. The first launch attempt on October 14 was scrubbed at T-31 seconds due to a failed Range Safety computer. The second launch attempt on October 15 was scrubbed at T-9 minutes due to failed a S-band transponder on the orbiter. Launch was reset for October 18. Countdown proceeded smoothly to liftoff, delayed only by several seconds because of an aircraft in the launch zone.
Orbital Altitude & Inclination	155 nmi (287 km), 39.00 deg
Launch Weight (lb/kg)	256,097[a]/116,164
Landing & Postlanding Operations	November 1, 1993, 7:05:42 a.m. PST, Runway 22, Edwards Air Force Base. The orbiter returned to Kennedy Space Center on November 9 after a two-day trip.
Rollout Distance (ft/m)	9,640/2,938
Rollout Time (seconds)	61
Mission Duration	336 hr, 12 min, 32 sec
Landed Revolution No.	225
Mission Support	STDN
Primary Objective	Dedicated Spacelab Life Sciences research
Deployed Satellites	None

Table 3–82. STS-58 Mission Characteristics (Continued)

Experiments	SLS-2 mission using the Spacelab long module: The crew conducted 14 experiments in four areas: regulatory physiology, cardiovascular/cardiopulmonary, musculoskeletal, and neurosciences. Eight of the experiments focused on the crew, six on 48 rodents. The crew collected more than 650 different samples from themselves and the rodents, increasing the statistical base for life sciences research. Cardiovascular/cardiopulmonary experiments: These experiments focused on understanding and quantifying the changes occurring on orbit and on the acute fluid shift and long-term adaptation of the heart and lungs. • Inflight Study of Cardiovascular Deconditioning • Cardiovascular Adaptation to Zero Gravity • Pulmonary Function During Weightlessness Regulatory physiology experiments: These experiments investigated the theory that the kidneys and endocrine glands adjusted the body's fluid-regulating hormones to stimulate an increase in fluid to be excreted. The experiments also investigated the mechanisms surrounding the decrease in red blood cells responsible for carrying oxygen to the tissues that occurred in spaceflight. • Fluid-Electrolyte Regulation During Spaceflight • Regulation of Blood Volume During Spaceflight • Regulation of Erythropoiesis in Rats During Spaceflight • Influence of Spaceflight on Erythrokinetics in Man Neuroscience investigations: These investigations documented both physical vestibular (balance) changes and perception changes and investigated the mechanisms involved. The investigators also hoped to identify countermeasures to alleviate the effects of space motion sickness. The mission included an Astronaut Science Advisor (ASA), a computer-based intelligent assistant designed to help astronauts work more efficiently and improve the quality of space science. The ASA supported the Rotating Dome Experiment, which measured how the visual and vestibular systems interact and how this interaction was affected as humans adapt to microgravity. The experiment included: • Study of the Effects of Space Travel on Mammalian Gravity Receptors • Vestibular Experiments in Spacelab

Table 3–82. STS-58 Mission Characteristics (Continued)

Experiments	Musculoskeletal investigations: In microgravity, the body's bones and muscles were used less extensively than on Earth. As a result, researchers saw a decrease in the mass of both during spaceflight. The SLS-2 studies provided more information about the complex musculoskeletal system, including: • Protein Metabolism During Spaceflight • Effects of Zero Gravity on the Functional and Biochemical Properties of Antigravity Skeletal Muscle • Effects of Microgravity on the Electron Microscopy, Histochemistry, and Protease Activities of Rat Hindlimb Muscles • Pathophysiology of Mineral Loss During Spaceflight • Bone, Calcium, and Spaceflight OARE: See STS-40. SAREX: See STS-35. Pilot Inflight Landing Operations Trainer (PILOT): The PILOT, a portable laptop computer simulator, allowed the pilot and commander to maintain proficiency for approach and landing during longer missions.
Get Away Specials	None
Mission Results	Successful

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[a] Jenkins, p. 302.

Table 3–83. STS-61 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Richard O. Covey PLT: Kenneth D. Bowersox PCF: Story Musgrave MS: Kathryn C. Thornton, Claude Nicollier (ESA), Jeffrey A. Hoffman, F. Story Musgrave, Thomas D. Akers
Launch	December 2, 1993, 4:27:00 a.m. EST, Kennedy Space Center, Pad 39-B. The launch was originally scheduled to occur from Launch Pad 39-A, but after rollout on October 28, contamination was found in the Pad 39-A Payload Changeout Room, and a decision was made to move the Shuttle and payloads to Pad 39-B. Rollaround occurred on November 15. The first launch attempt on December 1 was scrubbed due to out-of-limit weather conditions at the Shuttle Landing Facility in the event of a return-to-launch-site contingency. Launch on December 2 occurred on schedule.
Orbital Altitude & Inclination	321 nmi (594 km), 28.45 deg
Launch Weight (lb/kg)	250,314/113,541
Landing & Postlanding Operations	December 13, 1993, 12:25:37 a.m. EST, Runway 33, Kennedy Space Center. Second night landing at Kennedy Space Center. The orbiter returned one orbit earlier than originally planned to allow two landing opportunities at Kennedy Space Center.
Rollout Distance (ft/m)	7,922/2,415
Rollout Time (seconds)	53
Mission Duration	259 hr, 58 min, 37 sec
Landed Revolution No.	162
Mission Support	STDN
Primary Objective	First Hubble Space Telescope Servicing Mission
Deployed Satellites	Hubble Space Telescope retrieved and redeployed after servicing
Experiments	None
Get Away Specials	None
Mission Results	Successful

Table 3–83. STS-61 Mission Characteristics (Continued)

Remarks	The record-setting five back-to-back spacewalks totaled 35 hours, 28 minutes. EVA No.1, by Hoffman and Musgrave, lasted 7 hours, 54 minutes. The two spacewalkers replaced two sets of remote sensing units, which contained gyroscopes that helped the Hubble Space Telescope point in the correct direction. They also replaced two electronic control units and eight electrical fuse plugs protecting the telescope's electrical circuits. This was the second longest spacewalk in U.S. history to date. EVA No. 2, by Akers and Thornton, lasting 6 hours, 36 minutes, replaced the telescope's two solar arrays. EVA No. 3, by Hoffman and Musgrave, lasted 6 hr, 47 minutes. They replaced the original WF/PC with a new WFPC-2 in about 40 minutes rather than the 4 hours that had been anticipated. The new camera had a higher rating than the previous model, especially in the ultraviolet range, and included its own spherical aberration correction system. They also replaced two magnetometers. EVA No. 4, by Akers and Thornton, lasting 6 hrs, 50 minutes, replaced the Hubble Space Telescope's High Speed Photometer (HSP) with the COSTAR system. COSTAR corrected the telescope's spherical aberration of the main mirror for all instruments except WFPC-2, which had its own built-in corrective optics. During this spacewalk, Akers set a new individual U.S. spacewalking record of 29 hours, 14 minutes. EVA No. 5, by Hoffman and Musgrave, lasted 7 hrs, 21 minutes. This EVA replaced the solar array drive electronics and, after several unsuccessful commands from the Space Telescope Operations Control Center, the astronauts cranked the solar arrays' deployment mechanism by hand, successfully deploying them. They also installed the GHRS Redundancy Kit and protective covers over the original magnetometers. The covers, which were fabricated on board by astronauts Nicollier and Bowersox, would contain any debris caused by the older magnetometers, which showed some signs of ultraviolet decay.

Table 3–84. STS-60 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Charles F. Bolden, Jr. PLT: Kenneth S. Reightler, Jr. MS: N. Jan Davis, Ronald M. Sega, Franklin R. Chang-Diaz, Sergei K. Krikalev (Russian Space Agency/RSA)
Launch	February 3, 1994, 7:10:00 a.m. EST, Kennedy Space Center, Pad 39-A. Launch was on time.
Orbital Altitude & Inclination	191 nmi (354 km), 57.00 deg
Launch Weight (lb/kg)	245,767[a]/111,478
Landing & Postlanding Operations	February 11, 1994, 2:19:22 p.m. EST, Runway 15, Kennedy Space Center. The first landing attempt was waved off due to unfavorable weather in the Kennedy Space Center area.
Rollout Distance (ft/m)	7,771/2,368
Rollout Time (seconds)	50
Mission Duration	199 hr, 9 min, 22 sec
Landed Revolution No.	129
Mission Support	STDN
Primary Objective	Experimentation using WSF-1 and SPACEHAB 02
Deployed Satellites	WSF-1: There were two unsuccessful attempts to deploy the facility. The WSF-1 was instead operated at the end of the remote manipulator system arm.
Experiments	SPACEHAB 02: SPACEHAB 02 carried 12 payloads conducted under the Commercial Middeck Augmentation Module contract. The experiments represented a wide range of space experimentation including nine commercial-development-of-space experiments in materials processing and biotechnology sponsored by five NASA CCDS; three supporting hardware and technology development payloads, one from a CCDS, one from Lewis Research Center; and one from Johnson Space Center. In addition, a Sample Return Experiment sat on the top of the SPACEHAB module. SPACEHAB 02 Payloads:[b] • SPACEHAB (ECLiPSE): This experiment used a rack-mounted, enclosed furnace assembly to investigate controlled liquid-phase sintering of metallic systems in microgravity. • Space Experiment Furnace: This payload allowed up to three separate furnaces in one unit. This flight carried one transparent furnace and one opaque core furnace.

Table 3–84. STS-60 Mission Characteristics (Continued)

Experiments	• ASTROCULTURE™: This payload validated the performance of plant growth technologies in the microgravity environment of space. • BPL: This experiment determined the response of cells to various hormones and stimulating agents in microgravity. • CGBA: The apparatus allowed a wide range of sophisticated biomaterials, life sciences, and biotechnology investigations to be performed in one device in a microgravity environment. It processed biological fluids by mixing components in a microgravity environment. The CGBA also supported 32 separate commercial investigations in the areas of biomedical testing and drug development, controlled ecological life support system development, and agricultural development and manufacture of biological-based materials. • IMMUNE-1: This experiment was designed to reduce or prevent changes seen in the immune system of 12 rats after spaceflight. The drug PEG-IL2 was used in an attempt to alleviate the immunosuppression induced by the microgravity environment. The experiment might provide a new therapy to treat the effects of spaceflight on the human immune system, as well as on physiological systems affected by the immune system. • ORSEP: This experiment explored the use of phase separation techniques in microgravity conditions to separate cells, cell fragments, and heavy molecules. • CPCG: This experiment was designed to produce large, well-ordered crystals of various proteins. See STS-49. • Penn State Biomodule: This was a computer-controlled, fluid-transfer mixing device used to test the hypothesis that exposure to near-zero gravity can alter microbial gene expression in commercially useful ways. • 3-DMA: The accelerometer helped chart the effects of deviations of zero gravity on experiments conducted in space, allowing researchers to review experiment results against deviations from zero gravity. • SAMS: The SAMS measured and recorded low-level accelerations during experiment operations. • Stirling Orbiter Refrigerator Freezer (SOR/F): The experiment was a flight test and characterization relating to operation of advanced refrigerator/freezer technology in microgravity. • Sample Return Experiment: This experiment sat on top of the SPACEHAB module to capture intact cosmic dust particles as they came in contact with 160 capture cells. The capture cells consisted of transparent silica aerogel, the lowest density solid material known with extremely fine structure.

Table 3–84. STS-60 Mission Characteristics (Continued)

Get Away Specials	G-071 Customer: California State University, Northridge OBBEX: This apparatus tested the effects of melting cylindrical metal alloy pellets in microgravity to produce a new kind of ball bearing never before built, a seamless hollow ball bearing. G-514 Customer: Goddard Space Flight Center The Orbiter Stability Experiment: The objective was to measure the vibration spectrum of the orbiter structure present during normal orbiter and crew operations and to evaluate fogging of photographic emissions due to energetic particles. G-536 Customer: NASA Headquarters, OSSA, Microgravity Sciences Division The Pool Boiling Experiment: This experiment marked the 100th GAS payload to fly since the program's inception. The experiment's objective was to improve understanding of the boiling process in microgravity. G-557 Customer: ESA The Netherlands Capillary Pumped Loop (CPL) Experiment: This experiment demonstrated in-orbit the working principle and performances of a two-phase CPL, a two-phase Vapor Quality Sensor, and a two-phase multichannel Condenser Profile. It also compared data on CPL behavior in a low-gravity environment with analytical predictions resulting from modeling and on-Earth performance. CAPL/ODERACS/BREMSAT/GAS Bridge Assembly • Capillary Pumped Loop (CAPL): This system investigated heat rejection in microgravity as a prototype of the two-phase thermal control system planned for use in the Earth Observing System (EOS) platform. This flew as a Hitchhiker payload. • ODERACS: This experiment deployed six spheres that were observed, tracked, and recorded by ground-based radars and optical telescopes.

Table 3–84. STS-60 Mission Characteristics (Continued)

Get Away Specials	• BREMEN Satellite (BREMSAT): The satellite conducted scientific activities at various mission phases. This German-built, ejectable satellite consisted of six scientific experiments operated before and after satellite deployment. The experiments measured heat conductivity; residual acceleration forces; density distribution and dynamics of micrometeorites and dust particles in low-Earth orbit; atomic oxygen; exchange of momentum and energy between the molecular flow and the rotating satellite; and pressure and temperature during reentry.
Mission Results	The WSF was not deployed but was operated at the end of the robot arm. Other mission objectives were successfully achieved.

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[a] Jenkins, p. 302.

[b] "Space Shuttle Mission STS-60 Press Kit" (February 1994, with Errata and Updates from January 27, 1994, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_060_STS-060_Press_Kit.pdf* (accessed December 2, 2005).

Table 3–85. STS-62 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: John H. Casper PLT: Andrew M. Allen MS: Pierre J. Thuot, Charles D. Gemar, Marsha S. Ivins
Launch	March 4, 1994, 8:53:00 a.m. EST, Kennedy Space Center, Pad 39-B. Launch set for March 3 was postponed at the T-11 hour mark due to predicted unfavorable weather in the Kennedy Space Center area. The countdown on March 4 proceeded smoothly. The only deviation to normal operating procedures was a delay in deploying the solid rocket booster recovery ships because of high seas. The recovery ships left port on launch day and recovered the boosters and their parachutes on March 6.
Orbital Altitude & Inclination	162 nmi (300 km) and 140 nmi (259 km), 39.00 deg
Launch Weight (lb/kg)	256,584[a]/116,385
Landing & Postlanding Operations	March 18, 1994, 8:09:41 a.m. EST, Runway 33, Kennedy Space Center.
Rollout Distance (ft/m)	10,151/3,094
Rollout Time (seconds)	55
Mission Duration	335 hr, 16 min, 41 sec
Landed Revolution No.	223
Mission Support	STDN
Primary Objective	Experimentation using USMP-2 and OAST-2
Deployed Satellites	None
Experiments	USMP-2: These experiments investigated materials processing and crystal growth in microgravity. • Advanced Automated Directional Solidification Furnace (AADSF) • MEPHISTO • Isothermal Dendritic Growth Experiment (IDGE) • Critical Fluid Light Scattering Experiment (ZENO) • SAMS

Table 3–85. STS-62 Mission Characteristics (Continued)

Experiments	OAST-2: The objective of this payload was to obtain technology data to support future needs for advanced satellites, sensors, microcircuits, and the ISS. Six In-Space Technology Program (INSTEP) experiments were mounted on a Hitchhiker carrier. • Experimental Investigation of Spacecraft Glow (EISG) and Spacecraft Kinetic Infrared Test (SKIRT): These experiments developed an understanding of the physical processes leading to the spacecraft glow phenomena by studying infrared, visible, and far-ultraviolet light emissions as a function of surface temperature and orbital altitude. • Cryogenic Two Phase (CRYOTP): This experiment determined the performance of microgravity nitrogen space heat pipe and cryogenically-cooled, vibration-free, phase-change-material thermal storage unit thermal energy control technologies. • Thermal Energy Storage (TES): This experiment determined the microgravity behavior of two different thermal energy storage salts that underwent repeated melting and freezing. • Emulsion Chamber Technology (ECT): This experiment measured background cosmic ray radiation as a function of shielding and radiation energy photographic films. • Solar Array Module Plasma Interaction Experiment (SAMPIE): This experiment determined the arcing and current collection behavior of different types, sizes, and shapes of solar cells, solar modules, and spacecraft materials. Dexterous End Effector (DEE): The DEE worked with the remote manipulator system and demonstrated a Force Torque Sensor, Magnetic End Effector, Targeting and Reflective Alignment Concept (TRAC) grapple alignment system, and Auto TRAC Vision System. SSBUV/A: See STS-34. LDCE: This experiment exposed material samples to atomic oxygen in the space environment. Advanced Protein Crystal Growth (APCG): This experiment produced high-quality, well-ordered crystals of selected proteins for analysis of molecular structures through x-ray diffraction and computer modeling. PSE: See STS-52. CPCG: See STS-49. CGBA: See STS-54. MODE: See STS-40.

Table 3–85. STS-62 Mission Characteristics (Continued)

Experiments	Bioreactor Demonstration Systems (BDS): This experiment attempted to determine the threshold mass for the transfer/diffusion of glucose and oxygen into a static cell culture in the microgravity environment. APE-B: See STS-33. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful

[a] Jenkins, p. 302.

Table 3–86. STS-59 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Sidney M. Gutierrez PLT: Kevin P. Chilton PC: Linda M. Godwin MS: Jerome Apt, Michael R. Clifford, Thomas D. Jones
Launch	April 9, 1994, 7:05:00 a.m. EDT, Kennedy Space Center, Pad 39-A. Launch set for April 7 was postponed for one day at the T-27-hour mark to allow for additional inspections of the metallic vanes in the SSME high-pressure oxidizer preburner pumps. Launch on April 8 was scrubbed due to weather, high crosswinds, and low clouds at the Shuttle Landing Facility and clouds at the launch pad. The countdown April 9 proceeded smoothly.
Orbital Altitude & Inclination	121 nmi (224 km), 57.00 deg
Launch Weight (lb/kg)	246,851[a]/111,970
Landing & Postlanding Operations	April 20, 1994, 9:54:30 a.m. PDT, Runway 22, Edwards Air Force Base. Landing was originally planned for Kennedy Space Center on April 19, but two landing opportunities were waved off due to low clouds and possible thunderstorms in the area. An early landing opportunity on April 20 was also waved off in favor of landing at Edwards Air Force Base. The orbiter returned to Kennedy Space Center from Edwards by Shuttle Carrier Aircraft on May 2, 1994.
Rollout Distance (ft/m)	10,691/3,258
Rollout Time (seconds)	54
Mission Duration	269 hr, 49 min, 30 sec
Landed Revolution No.	182
Mission Support	STDN
Primary Objective	Study Earth's global environment using SRL-1
Deployed Satellites	None

Table 3–86. STS-59 Mission Characteristics (Continued)

Experiments	SRL-1: This was the first simultaneous multifrequency (C, L, and X bands), multipolarization phased-array imaging radar in space for geoscientific studies of Earth in different seasons. Used to image sites for geology, hydrology, vegetation science, and oceanography to study vegetation type, extent, and deforestation; water storage and flux; ocean dynamics; wave fields; wind fields; volcanism; tectonic activity; soil erosion; desertification; and topography. The SRL payload consisted of: • SIR-C • X-SAR • MAPS The DARA and the Italian Space Agency provided the X-SAR instrument.
	CONCAP-IV: See STS-57.
	STL/National Institutes of Health-Cells (NIH)-C: Configuration A and B–These experiments validated models for muscle, bone, and endothelial cell biochemical and functional loss induced by microgravity stress; to evaluate cytoskeleton, metabolism, membrane integrity, and protease activity in target cells; and to test tissue loss pharmaceuticals for efficacy.
	VFT-4: This test measured the near and far point of clear vision, as well as the ability to change focus within the range of clear vision.
	SAREX-II: See STS-35.
Get Away Specials	G-203 Customer: New Mexico State University G-203 observed the crystal forming characteristics of water using zeolite desorption-absorption processing.
	G-300 Customer: Matre/Laboratoire de Genie Electrique de Paris (L.G.E.P.) G-300 performed conductivity measurements on two silicon oils in microgravity.
	G-458 Customer: The Society of Japanese Aerospace Companies, Inc. G-458 cultivated cellular slime molds.
Mission Results	Successful

[a] Jenkins, p. 302.

Table 3–87. STS-65 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Robert D. Cabana PLT: James D. Halsell, Jr. PC: Richard J. Hieb MS: Carl E. Walz, Leroy Chiao, Donald A. Thomas PS: Chiaki Naito-Mukai (JAXA).
Launch	July 8, 1994, 12:43:00 p.m. EDT, Kennedy Space Center, Pad 39-A. The launch occurred exactly on time at the beginning of a 2 1/2-hour launch window. The countdown progressed smoothly but was held at T-9 minutes due to a return-to-launch-site weather constraint. The weather constraint was cleared at 12:36 p.m., leading to an on-time liftoff.
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	258,585[a]/117,292
Landing & Postlanding Operations	July 23, 1994, 6:38:00 a.m. EDT, Runway 33, Kennedy Space Center. This was the longest Shuttle flight to date. The landing opportunity on July 22 was waved off due to the possibility of rain showers in the area.
Rollout Distance (ft/m)	10,211/3,112
Rollout Time (seconds)	68
Mission Duration	353 hr, 55 min, 1 sec
Landed Revolution No.	234
Mission Support	STDN
Primary Objective	IML-2
Deployed Satellites	None

Table 3–87. STS-65 Mission Characteristics (Continued)

Experiments	IML-2: Two teams performed around-the-clock research. The space agencies represented were: NASA; ESA; CSA; the Centre National d'Etudes spatiales (CNES); DARA; and the NASDA. The activities were divided into two groups: life sciences and microgravity sciences and used a number of facilities and apparatus. Life science apparatus included: • Biorack • Biostack • EDOMP • Spinal Changes in Microgravity (SCM) • NIZEMI • Aquatic Animal Experiment Unit (AAEU) • Free Flow Electrophoresis Unit (FFEU) • Real-time Radiation Monitoring Device (RRMD) • Thermoelectric Incubator (TEI)/Cell Culture Kit (CCK) • Performance Assessment Workstation (PAWS) Microgravity science apparatus included: • APCF • Bubble, Drop and Particle Unit (BDPU) • CPF • Large Isothermal Furnace (LIF) • Quasi-Steady Acceleration Measurement System (QSAMS) • Applied Research on Separation Methods Using Space Electrophoresis (RAMSES) • SAMS • TEMPUS • Vibration Isolation Box Experiment System (VIBES) OARE: See STS-40. CPCG: See STS-49. Military Application of Ship Tracks (MAST): This experiment used Linhof and Hasselblad cameras to detect ship movement by detecting ship tracks formed in stratus, stratocumulus, and fog when ship-induced disturbances and emissions altered existing cloud structures. SAREX: See STS-35. AMOS Calibration Test: See STS-29.
Get Away Specials	None
Mission Results	Successful
Remarks	The crew took time during the mission to honor the 25th anniversary of Apollo 11, noting that Apollo 11 also featured a spacecraft named *Columbia*. *Columbia* was outfitted with extended duration orbiter hardware for the flight.

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[a] Jenkins, p. 302.

Table 3–88. STS-64 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Richard N. Richards PLT: L. Blaine Hammond, Jr. MS: Jerry M. Linenger, Susan J. Helms, Carl J. Meade, Mark C. Lee
Launch	September 9, 1994, 6:22:55 p.m. EDT, Kennedy Space Center, Pad 39-B. A late afternoon launch was scheduled to permit nighttime operation of the LITE laser early in the mission. The launch was delayed due to launch weather violations near the launch complex.
Orbital Altitude & Inclination	140 nmi (259 km), 57.00 deg
Launch Weight (lb/kg)	241,434/109,513
Landing & Postlanding Operations	September 20, 1994, 5:12:52 p.m. EDT, Runway 04, Edwards Air Force Base. Mission already extended one day was extended again after first landing opportunities at Kennedy Space Center on September 19 were waved off due to stormy weather. Two additional opportunities at Kennedy Space Center on September 20 were also waved off, and the orbiter was diverted to California. The orbiter was transported to Kennedy Space Center on September 27.
Rollout Distance (ft/m)	9,656/2,943
Rollout Time (seconds)	60
Mission Duration	262 hr, 49 min, 57 sec
Landed Revolution No.	175
Mission Support	STDN
Primary Objective	Experimentation using the LIDAR LITE: Deployment and retrieval of SPARTAN-201
Deployed Satellites	Deployed and retrieved SPARTAN-201
Experiments	LITE: This experiment measured the vertical profile of certain atmospheric parameters (cloud top height, planetary boundary layer height, tropospheric aerosols, stratospheric aerosols, temperature, and density). These measurements were obtained by emitting laser energy into the atmosphere and measuring the return signals scattered from the atmospheric constituents. Unprecedented views were obtained of cloud structures, storm systems, dust clouds, pollutants, forest burning, and surface reflectance. Sites studied included the atmosphere above northern Europe, Indonesia and the south Pacific, Russia, and Africa.

Table 3–88. STS-64 Mission Characteristics (Continued)

Experiments	Shuttle Plume Impingement Flight Experiment (SPIFEX): The SPIFEX studied the characteristics and behavior of exhaust plumes from *Discovery*'s Reaction Control System thrusters during the mission. The SPIFEX, when picked up by *Discovery*'s mechanical arm, is a 33-ft (10-m)-long extension for the arm with a package of instruments to measure the near-field, transition, and far-field effects of thruster plumes. The SPIFEX plume information gathered would assist planners in understanding the potential effects of thruster plumes on large space structures, such as the Russian *Mir* space station and the ISS, during future Shuttle docking and rendezvous operations. SAREX-II: See STS-35. SSCE: See STS-41. Biological Research in Canister (BRIC): This experiment investigated the effects of spaceflight on small arthropod animals and plant specimens. RME-III: See STS-28. MAST: See STS-59. AMOS Calibration Test: See STS-29. Robot Operated Materials Processing Systems (ROMPS): These systems used the microgravity environment to develop commercially valuable methods of processing semiconductor materials. ROMPS also advanced automation and robotics for material processing in ways that could lower the costs of developing and manufacturing semiconductors. The ROMPS experiment investigated in-space processing of semiconductor materials and consisted of a robot, furnace, samples, and control electronics. It used the robot to transport a variety of semiconductors from the storage racks to halogen lamp furnaces where their crystal structures were reformed in heating and cooling cycles. ROMPS flight hardware was contained in a pair of GAS cans mounted on the Hitchhiker-G Carrier. ROMPS was the first robotics system operated in space. The NASA Office of Advanced Concepts and Technology sponsored ROMPS as part of their mission to develop commercially relevant techniques for in-space materials processing. The project was being carried out by Goddard Space Flight Center and two NASA-sponsored Centers for the Commercial Development of Space: the Consortium for Commercial Crystal Growth at Clarkson University in Potsdam, New York, and the Space Automation and Robotics Center in Ann Arbor, Michigan.

Table 3–88. STS-64 Mission Characteristics (Continued)

Get Away Specials	GBA: This assembly held 10 GAS canisters containing experiments to investigate different physical and biological phenomena and two ballast GAS cans containing accelerometers. G-178 Customer: Sierra College, Rocklin, California Spectrometer Measurements of the Upper Atmosphere in the UV Range: G-178 took ozone measurements of Earth's upper atmosphere in the ultraviolet 200-nanometer to 400-nanometer spectral range using a Charge Coupled Device (CCD)-based spectrometer. A CCD photographic camera also flew as part of the experiment and provided target verification for the spectrometer. G-254 Customer: The Kinkaid School and Utah State University Four experiments were flown in individual spacepaks, including a new aluminum Isogrid construction. The payload contained popcorn kernels and radish seeds in separate Ziploc bags as an experiment by Edith Bowen Elementary School located on the Utah State University campus. After the flight, the students popped and tasted the popcorn. The radishes were grown and compared with a similar sample maintained in 1g. The experiments dealt with fluid distillation, flat zone instability, photosynthesis, and bubble interferometry. G-0325 Customer: Norfolk, Virginia Public Schools NORSTAR experiment: Acoustic Wave Study and 60 minor experiments: This experiment recorded visually how sound affected dust particles in near-zero gravity to advance understanding of acoustics. G-417 Customer: Beijing Institute of Environmental Engineering Three experiments: Paramecium Reproduction, Oil and Water Mixing, Soldering Examples.

Table 3–88. STS-64 Mission Characteristics (Continued)

Experiments	G-453 Customer: N. Tateyama, The Society of Japanese Aerospace Co., Inc. (SJAC) Reflight of G-453 on STS-57 due to incomplete results following a battery failure. The experiments investigated the formation of superconducting material and the boiling phenomenon under microgravity and the absence of convection. There were two experiments: 1) Formation of Silicon-Lead (Si-Pb) Alloy: This experiment investigated the formation of superconducting alloy (not mixable on the ground). Each sample, in a platinum crucible located inside a quartz ampoule (small glass container), was heated in a furnace up to 1,450°C (2,640°F) for 25 minutes. 2) Boiling Experiment: This experiment observed the bubble formation when an organic solvent (Freon 113) boiled under microgravity and in the absence of convection. The organic solvent was heated and boiled in a small sealed vessel. The behavior of bubbles formed while boiling was observed and recorded using a video system. G-454 Customer: Society of Japanese Aerospace Co. Crystallization via a Temperature Gradient Furnace: G-454 investigated the crystallization or the formation of materials under microgravity and in the absence of convection. G-456 Customer: Society of Japanese Aerospace Co. Separation of Biologically Active Materials via Electrophoresis: G-456 observed electrophoresis (the movement of suspended particles through a fluid or gel under the action of an electromotive force applied to electrodes in contact with the suspension) with a video camera above the separation chamber. The experiment was recorded on video cassette recorders. The separation results would be compared to results obtained on Earth. G-485 Customer: ESA Material Evaporation/Exposure experiment via a motorized door assembly: This experiment tested the feasibility of depositing different materials in a microgravity and vacuum environment by flying the payload in a GAS canister with a motorized door assembly.

Table 3–88. STS-64 Mission Characteristics (Continued)

Experiments	G-506 Customers: Goddard Space Flight Center and Morgan State University Three experiments: Orbiter Stability Experiment: This experiment was designed to evaluate the Space Shuttle as a platform for imaging the Sun in x-rays and extreme ultraviolet light. Radiation Effects on Photographic Film. Radiation Effects on Seeds: This experiment studied the effects of radiation and zero gravity on germination and growth. G-562 Customer: Canadian Space Agency QUESTS: Reflight of G-521: G-562 consisted of 12 isothermal furnaces and three gradient furnaces for materials science, a computer control system, a data acquisition system, and batteries. There were two types of furnaces: temperature-gradient (for directional crystal growth studies) and constant-temperature (for metal diffusion studies). Sample Return Experiment: The experiment sat on top of the GAS can in position 4. The primary science objective was to quantify extraterrestrial particles and other orbital debris in the orbiter bay. A secondary objective was a realistic test for comet sample collection concepts.
Mission Results	Successful
Remarks	Astronauts Lee and Meade completed the first untethered EVA in a decade. During the 6-hour, 15-minute EVA, they tested a new SAFER backpack designed for use in the event a crew member became untethered while conducting an EVA.

Table 3–89. STS-68 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Michael A. Baker PLT: Terrence W. Wilcutt PC: Thomas D. Jones MS: Steven L. Smith, Daniel W. Bursch, Peter J.K. Wisoff
Launch	September 30, 1994, 7:16:00 a.m. EDT, Kennedy Space Center, Pad 39-A. The first launch attempt August 18 was halted at T-1.9 seconds when orbiter computers shut down all three main engines after detecting an unacceptably high discharge temperature in the high-pressure oxidizer turbopump turbine for main engine No. 3. *Endeavour* returned to the VAB and all three engines were replaced. The countdown for the second launch attempt proceeded smoothly to an on-time liftoff September 30.
Orbital Altitude & Inclination	120 nmi (222 km), 57.00 deg
Launch Weight (lb/kg)	247,129/112,096
Landing & Postlanding Operations	October 11, 1994, 10:02:08 a.m. PDT, Runway 22, Edwards Air Force Base. The landing was diverted to Edwards Air Force Base because of unacceptable weather at Kennedy Space Center. The postlanding video showed what appeared to be water dripping from the area of the centerline latch for the orbiter/external tank doors. The source later was found to be a cracked valve in water spray boiler No. 3. The orbiter returned to Kennedy Space Center atop the 747 Shuttle Carrier Aircraft October 2.
Rollout Distance (ft/m)	8,495/2,589
Rollout Time (seconds)	60
Mission Duration	269 hr, 46 min, 8 sec
Landed Revolution No.	181
Mission Support	STDN
Primary Objective	Research using the SRL-2
Deployed Satellites	None

Table 3–89. STS-68 Mission Characteristics (Continued)

Experiments	SRL-2: The SRL-2 was the second simultaneous multfrequency (C, L, and X bands), multipolarization phased array imaging radar in space for geoscientific studies of Earth's different seasons. The crew used the SRL-2 to image sites for geology, hydrology, vegetation science, and oceanography to study vegetation type, extent, and deforestation; water storage and flux; ocean dynamics; wave fields; wind fields; volcanism; tectonic activity; soil erosion; desertification; and topography. Using SIR-C/X-SAR, the crew imaged a volcanic eruption in Russia and the islands of Japan after an earthquake. The SRL-2 payload consisted of the following: • SIR-C • X-SAR • MAPS The DARA and Italian Space Agency provided the X-SAR instrument.
	CHROMEX: See STS-29.
	CPCG: See STS-49.
	BRIC: See STS-64.
	CREAM: See STS-48.
	MAST: See STS-65.
Get Away Specials	G-316 Customer: North Carolina A&T State University This experiment determined the effect of microgravity on arthropod development and crystal growth.
	G-503 Customer: University of Alabama This experiment determined the effect of microgravity on diatoms, the curing of concrete, root growth, and the pitting of metals.
	G-541 Customer: Swedish Space Corporation This experiment studied the breakdown of a planar solid/liquid interface in space.
	GAS Postal Payloads: The U.S. Postal Service used GAS hardware to fly 500,000 commemorative stamps to recognize the 25th anniversary of the Apollo 11 Moon Landing. The stamp was a $9.95 Express Mail stamp. Father and son team Paul and Chris Calle, experienced stamp designers and NASA Art Program participants, created the artwork for the stamp.

Table 3–89. STS-68 Mission Characteristics (Continued)

Get Away Specials	Sample Return Experiments Principal Investigator: Dr. Peter Tsou, Jet Propulsion Laboratory Two Sample Return Experiments sat on top the postal payloads. The primary science objective was the quantification of extraterrestrial particles and other orbital debris present in the orbiter bay. A secondary objective was a realistic test for comet sample collection concepts.
Mission Results	Successful

Table 3–90. STS-66 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Donald R. McMonagle PLT: Curtis L. Brown, Jr. PC: Ellen Ochoa MS: Joseph R. Tanner, Jean-Francois Clervoy (ESA), Scott E. Parazynski
Launch	November 3, 1994, 11:59:43 a.m. EST, Kennedy Space Center, Pad 39-B. The 11:56 a.m. launch was delayed slightly while Shuttle managers assessed the weather at the transoceanic abort landing sites. The liftoff was *Atlantis*'s first since an extended checkout and modification period at the Rocketdyne Rockwell plant in Palmdale, California.
Orbital Altitude & Inclination	164 nmi (304 km), 57.00 deg
Launch Weight (lb/kg)	243,089[a]/110,263
Landing & Postlanding Operations	November 14, 1994, 7:33:45 a.m. PST, Runway 22, Edwards Air Force Base. The landing was diverted to California due to high winds, rain, and clouds in Florida from Tropical Storm Gordon.
Rollout Distance (ft/m)	7,642/2,329
Rollout Time (seconds)	49
Mission Duration	262 hr, 34 min, 2 sec
Landed Revolution No.	173
Mission Support	STDN
Primary Objective	Research using ATLAS-3; deployment and retrieval of the CRISTA-SPAS
Deployed Satellites	Deployed and retrieved CRISTA-SPAS: The spacecraft carried two instruments—the German CRISTA telescope and the U.S. Middle Atmosphere High Resolution Spectrograph Investigation (MAHRSI) instrument.

Table 3–90. STS-66 Mission Characteristics (Continued)

Experiments	ATLAS-3: The ATLAS-3 collected data about the Sun's energy output and chemical makeup of Earth's middle atmosphere and how these factors affected global ozone levels. The experiments included the following: • ATMOS Experiment: This experiment collected data on trace gases in the atmosphere. • SSBUV: The spectrometer took ozone measurements to calibrate the NOAA-9 satellite ozone monitor. The SSBUV also took cooperative measurements with other ATLAS-3 instruments. (See STS-34.) • ACRIM: The ACRIM made extremely precise measurements of the Sun's total radiation for 30 orbits as a calibration reference for a sister instrument on the UARS launched in 1991. • SOLCON: Provided by Belgium, the SOLCON measured solar radiation as a reference point to track changes over years. • SOLSPEC: A French instrument. The SOLSPEC measured the Sun's radiation as a function of wavelength. • SUSIM: The SUSIM measured the fluctuation of the Sun's ultraviolet radiation and determined how much the measured ultraviolet light degraded the accuracy of the measuring instrument. • MAS: The MAS collected 9 hours of observations, measuring the distribution of water vapor, chlorine monoxide, and ozone at altitudes between 12 mi and 60 mi (20 km and 100 km) before a computer malfunction halted instrument operations. Experiment of the Sun Complementing the ATLAS Payload and Education-II (ESCAPE-II): This experiment collected solar data with solar imaging and ultraviolet solar irradiance experiments. The data was correlated with the co-manifested ATLAS-3 solar experiments to understand upper atmosphere photochemistry. Protein Crystal Growth-Thermal Enclosure System (PCG-TES): This experiment investigated the mechanisms of PCG and retrieved high-quality crystals grown during spaceflight using a double locker TES. Protein Crystal Growth-Single Locker Thermal Enclosure System (PCG-STES): This experiment investigated the mechanisms of PCG and retrieved high-quality crystals grown during spaceflight using a single locker TES. HPP Experiment-Reflight: See STS-52. PARE/NIH-R: Both PARE and NIH-R studied the physiological and anatomical changes occurring in mammals under weightless spaceflight conditions.

Table 3–90. STS-66 Mission Characteristics (Continued)

Experiments	SAMS: See STS-43. STL-A: See STS-53.
Get Away Specials	None
Mission Results	Successful
Remarks	This mission successfully tested a different method of approaching a spacecraft to retrieve CRISTA-SPAS as a prelude to the upcoming U.S. Shuttle/Russian space station *Mir* docking flights. Called an R-Bar approach, it was expected to save propellant while reducing the risk of contamination to *Mir* systems from orbiter thruster jet firings.

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[a] Jenkins, p. 302.

Table 3–91. STS-63 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: James D. Wetherbee PLT: Eileen M. Collins PC: Bernard A. Harris, Jr. MS: C. Michael Foale, Janice Voss, Vladimir G. Titov (RSA)
Launch	February 3, 1995, 12:22:04 a.m. EST, Kennedy Space Center, Pad 39-B. NASA adjusted the countdown sequence to accommodate a short 5-minute window required for rendezvous with *Mir*, including adding more hold time at T-6 hours and T-9 minutes. The launch first scheduled for February 2 was postponed on February 1 when one of the three inertial measurement units on the orbiter failed. The countdown on February 3 proceeded so smoothly that there was extra time left in the T-9-minute hold. The launch marked the first at a 51.6-degree inclination to the equator to put the orbiter into the same orbital plane as *Mir*.
Orbital Altitude & Inclination	213 nmi (394 km), 51.60 deg
Launch Weight (lb/kg)	247,555[a]/112,289
Landing & Postlanding Operations	February 11, 1995, 6:50:19 a.m. EST, Runway 15, Kennedy Space Center. This was the first end-of-mission landing since the runway was resurfaced in fall 1994 to decrease wear on orbiter tires and increase crosswind tolerances. After landing, cosmonauts aboard *Mir* radioed their congratulations to the *Discovery* crew. *Discovery* became the first orbiter in the U.S. fleet to complete 20 missions. The orbiter transferred to the OPF later that day.
Rollout Distance (ft/m)	11,002/3,353
Rollout Time (seconds)	80
Mission Duration	198 hr, 28 min, 15 sec
Landed Revolution No.	128
Mission Support	STDN
Primary Objective	Experimentation using SPACEHAB-3, deployment and retrieval of SPARTAN-204
Deployed Satellites	Deployed and retrieved SPARTAN-204 with Far Ultraviolet Imaging Spectrograph (FUVIS)

Table 3–91. STS-63 Mission Characteristics (Continued)

Experiments	SPACEHAB-3: This commercially developed module carried experiments in biotechnology and advanced materials development, technology demonstrations, and two pieces of supporting hardware measuring on-orbit accelerations. • Biotechnology experiments: – ASC-04 – BPL-03 – CGBA-06 – Fluids Generic Bioprocessing Apparatus (FGBA-01) – IMMUNE-02 – Commercial Protein Crystal Growth-Vapor Diffusion Apparatus (CPCG-VDA) – Protein Crystallization Facility-Light Scattering/Temperature Controlled (PCFLS/T) • Materials processing experiments were: – ECLiPSE-Hab – Gas Permeable Polymer Membranes (GPPM-02) Technology experiments: – 3-DMA Charlotte™ Robotic Experiment Monitor • Life and biomedical sciences and applications experiments: – BRIC-03 – CHROMEX-06 – NIH-C-03 • Microgravity science and applications experiments: – PCG-STES-03 – SAMS-03 • Johnson Space Center Space and Life Sciences Directorate experiment: – CPDS • DOD, U.S. Air Force experiments: – CREAM-06 – RME-III – Window Experiment (WINDEX-01) Cryo Systems Experiment (CSE): This experiment tested cryogenic cooling system and oxygen diode heat pipes for use on future spacecraft designs. GLO-2: See STS-53. ODERACS-2: See STS-53. SSCE: See STS-41. AMOS Calibration Test: See STS-29. IMAX: The crew used the IMAX handheld motion picture camera to film inside the crew cabin.
Get Away Specials	None
Mission Results	Successful

Table 3–91. *STS-63 Mission Characteristics (Continued)*

Remarks	Astronauts Foale and Harris began an EVA suspended at the end of the robot arm, away from the payload bay, to test modifications to their spacesuits to keep spacewalkers warmer in the extreme cold of space. They were then scheduled to practice handling the approximately 2,500-lb (1,134-kg) SPARTAN-204 to rehearse Space Station assembly techniques. However, both astronauts reported they were becoming very cold–this portion of EVA was performed during a night pass and mass-handling was curtailed. The EVA lasted 4 hours, 38 minutes. This was the first flight as part of Phase I of the ISS program. The Shuttle performed first approach and fly-around of Russian space station *Mir.*

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[a] Jenkins, p. 302.

Table 3–92. STS-67 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Stephen S. Oswald PLT: William G. Gregory MS: John M. Grunsfeld, Wendy B. Lawrence PC: Tamara E. Jernigan PS: Samuel T. Durrance, Ronald A. Parise
Launch	March 2, 1995, 1:38:13 a.m. EST, Kennedy Space Center, Pad 39-A. After a smooth countdown, liftoff was delayed for about a minute due to concerns about a heater system on the flash evaporator system. A backup heater was used, and the countdown proceeded.
Orbital Altitude & Inclination	187 nmi (346 km), 28.45 deg
Launch Weight (lb/kg)	256,293[a]/116,253
Landing & Postlanding Operations	March 18, 1995, 1:47:01 p.m. PST, Runway 22, Edwards Air Force Base. The orbiter was diverted to Edwards Air Force Base after landing opportunities in Florida were waved off on March 17 and in the early day on March 18. The orbiter returned to Florida on March 27 and was taken to the OPF on March 28.
Rollout Distance (ft/m)	9,975/3,040
Rollout Time (seconds)	59
Mission Duration	399 hr, 8 min, 48 sec
Landed Revolution No.	261
Mission Support	STDN
Primary Objective	Research using Astro-2
Deployed Satellites	None
Experiments	Astro-2: The Astro-2 made ultraviolet observations of stars, galaxies, magnetospheres, and quasars.[b] Three experiments were mounted to the SPACELAB instrument pointing system: • HUT: Considered a complement to the Hubble Space Telescope, the HUT completed more than 200 separate observations of more than 100 celestial objects. • WUPPE: The WUPPE greatly expanded the database on ultraviolet spectropolarimetry. • UIT: The UIT cameras imaged about two dozen large spiral galaxies for inclusion in an atlas of such galaxies; it made the first ultraviolet images of the entire Moon.

Table 3–92. STS-67 Mission Characteristics (Continued)

Experiments	Middeck Active Control Experiment (MACE): The MACE measured and controlled the dynamics of complex systems in the microgravity environment. The experiment developed a well verified set of Control Structure Integration/Controlled Structures Technology (CSI/CST) methods and approaches, allowing designers of future CST spacecraft, which cannot be dynamically tested on the ground in a sufficiently realistic zero-gravity simulation, to have confidence in the eventual orbit of such spacecraft. PCG-TES: See STS-66. PCG-STES: See STS-63. CMIX: See STS-56. SAREX-II: See STS-35.
Get Away Specials	G-387 and G-388 Customer: Australian Space Office and Auspace Limited G-387 and G-388 made ultraviolet observations of deep space to aid in the study of the structure of galactic supernova remnants, distribution of hot gas in the Magellanic Clouds, hot galactic halo emissions, and emissions associated with galactic cooling flows and jets.
Mission Results	One of the two cameras on the UIT malfunctioned undetected while on orbit, and only 80 percent of UIT's science objectives were met. Other mission objectives were met successfully.
Remarks	*Endeavour* was outfitted with extended duration orbiter hardware for the flight.

[a] Jenkins, p. 303.

[b] See chapter 4, Space Science, of this volume for further discussion of the Astro-2 mission.

Table 3–93. STS-71 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Robert L. Gibson PLT: Charles J. Precourt PC: Ellen S. Baker MS: Gregory J. Harbaugh, Bonnie J. Dunbar Anatoly Solovyev (RSA)–*Mir*-19 crew upload Nikolai Budarin (RSA)–*Mir*-19 crew upload Norman E. Thagard–*Mir*-18 crew download Vladimir Dezhurov (RSA)–*Mir*-18 crew download Gennadiy Strekalov (RSA)–*Mir*-18 crew download
Launch	June 27, 1995, 3:32:19 p.m. EDT, Kennedy Space Center, Pad 39-A. The launch was originally targeted for late May but slipped into June to accommodate Russian space program activities necessary for the first Space Shuttle–*Mir*–Space Station docking, including a series of spacewalks to reconfigure the Station for docking and launch of the new Spektr module to *Mir* containing U.S. research hardware. The launch set for June 23 was scrubbed when rainy weather and lightning prevented loading of the external tank earlier that day. A second try June 24 was scrubbed at T-9 minutes, again due to persistent stormy weather in central Florida, coupled with a short 10-minute launch window. Liftoff was reset for June 27, and final countdown proceeded smoothly.
Orbital Altitude & Inclination	170 nmi (315 km)/216 nmi (400 km) when docking, 51.60 deg
Launch Weight (lb/kg)	248,857[a]/112,880
Landing & Postlanding Operations	July 7, 1995, 10:54:34 a.m. EDT, Runway 15, Kennedy Space Center. The runway switched from 33 to 15 about 20 minutes before touchdown due to concerns of Chief Astronaut Robert Cabana, flying the Shuttle Training Aircraft, about clouds blocking runway landing aids from view.
Rollout Distance (ft/m)	8,364/2,549
Rollout Time (seconds)	51
Mission Duration	235 hr, 22 min, 17 sec
Landed Revolution No.	152
Mission Support	STDN
Primary Objective	First Shuttle-*Mir* docking
Deployed Satellites	None

Table 3–93. STS-71 Mission Characteristics (Continued)

Experiments	IMAX camera: This 70-mm motion picture camera system photographed rendezvous and spacecraft operations from within the crew compartment. SAREX-II: See STS-35.
Get Away Specials	None
Mission Results	Successful
Remarks	Spacelab-*Mir*: This was a combined science and logistical transfer mission. Life and microgravity science investigations were performed jointly with *Mir* to complement investigations on the Shuttle. The crews performed research into biomedical life sciences and microgravity with an emphasis on the effects of long-duration spaceflight on the human body. The logistical transfers included transporting the *Mir*-19 crew to *Mir*; returning the *Mir*-18 crew; transferring water to *Mir*; science specimens and hardware transferred to and from *Mir*; food resupply sent to *Mir*; and Russian hardware returned. The crews conducted fifteen separate biomedical and scientific investigations, covering seven different disciplines: 1) cardiovascular and pulmonary functions; 2) human metabolism; 3) neuroscience; 4) hygiene, sanitation, and radiation; 5) behavioral performance and biology; 6) fundamental biology; and 7) microgravity research. The *Mir*-18 crew served as test subjects for the investigations. The joint *Atlantis-Mir* spacecraft was the largest ever in orbit when the two were linked and the first on-orbit changeout of a Shuttle crew. Astronaut Thagard logged the longest U.S. spaceflight with his return from *Mir*. For the return flight, the crews made provisions on the *Atlantis* to accommodate an eight-person crew. President William J. Clinton called and congratulated the crews on the successful docking and invited them to visit the White House.

[a] Jenkins, p. 303.

Table 3–94. STS-70 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Terence T. Henricks PLT: Kevin R. Kregel MS: Nancy J. Currie (Sherlock), Donald A. Thomas, Mary Ellen Weber
Launch	July 13, 1995, 9:41:55 a.m. EDT, Kennedy Space Center, Pad 39-B. The count was held for 55 seconds at T-31 seconds due to fluctuations seen on the external tank automatic gain control external tank range safety system receiver. Launch Commit Criteria contingency procedures were worked and the count then proceeded on schedule. STS-70 had originally moved ahead of the launch of STS-71 because of a delay in the launch of the Russian Spektr laboratory module to the Russian space station *Mir*. However, on May 31, NASA Shuttle managers assessed damage to the *Discovery*'s external tank caused by nesting flicker woodpeckers. The damage consisted of about 71 holes (ranging in size from 0.5 in (1.3 cm) to 4 in (10 cm) in diameter) in the external tank's thermal protection foam insulation. Technicians installed safeguards against additional damage. On June 2, NASA managers decided to delay the launch of *Discovery* on STS-70 to repair the foam insulation on the vehicle's external tank. STS-71 was moved ahead of STS-70 and *Discovery* was rolled back to the VAB. It was the quickest turnaround landing (STS-71) to launch (STS-70).
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	258,798[a]/117,389
Landing & Postlanding Operations	July 22, 1995, 8:02:00 a.m. EDT, Runway 33, Kennedy Space Center. The first landing opportunities on July 21 at Kennedy Space Center were waved off due to fog and low visibility. The first opportunity on July 22 at Kennedy Space Center was also waved off.
Rollout Distance (ft/m)	8,465/2,580

Table 3–94. STS-70 Mission Characteristics (Continued)

Rollout Time (seconds)	57
Mission Duration	214 hr, 20 min, 7 sec
Landed Revolution No.	143
Mission Support	STDN
Primary Objective	Deployment of TDRS-G
Deployed Satellites	TDRS-G (7)/IUS
Experiments	PARE/NIH-R: See STS-66. Bioreactor Demonstration System (BDS): The BDS developed the capability and demonstrated the ability to grow mammalian cells in fluid growth medium in microgravity. CPCG: See STS-49. STL/NIH-C: See STS-59. BRIC: See STS-64. SAREX-II: See STS-35. VFT-4: See STS-59. HERCULES: This system provided an on-orbit capability to geolocate a ground target. MIS-B: See STS-53. WINDEX: The WINDEX obtained spectrally isolated images of the Shuttle surface glow, thruster plumes, water dumps, aurora, and airglow. RME-III: See STS-28. MAST: See STS-65.
Get Away Specials	None
Mission Results	Successful. It was the most trouble-free mission to date.[b]
Remarks	This was the first mission in which ground support used the new Mission Control Center at Johnson Space Center.[c]

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[a] Jenkins, p. 303.

[b] "STS-70/Flight 70 Mission Report," *http://members.aol.com/WSNTWOYOU/STS70MR.HTM* (accessed December 6, 2005).

[c] "STS-70 Flight Brings New Tools On-Line," *Space News Roundup*, Johnson Space Center 34, no. 28 (July 14, 1995): 1, *http://www.jsc.nasa.gov/history/roundups/issues/95-07-14.pdf* (accessed December 7, 2005).

Table 3–95. STS-69 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: David M. Walker PLT: Kenneth D. Cockrell PC: James S. Voss MS: James H. Newman, Michael L. Gernhardt
Launch	September 7, 1995, 11:09:00 a.m. EDT, Kennedy Space Center, Pad 39-A. The launch originally set for August 5 was postponed indefinitely to allow further review of solid rocket motor nozzle joint hardware from STS-70 and STS-71. An inspection team was formed to assess the significance of the gas path in nozzle internal joint No. 3, extending from insulation in the motor chamber to, but not past, the primary O-ring seal. The team concluded that the nozzle joint design was sound and that gas paths were being created when insulation material, known as Room Temperature Vulcanizing, was applied. Small air pockets were forming in the thermal insulation that could later become pathways for hot gas during motor operation. Attention then focused on developing procedures to allow Non-Destructive Evaluation (NDE) inspection of insulation at the pad, and a new launch date of August 31 was set. The August 31 launch was scrubbed about 5.5 hours before liftoff due to the failure of one of the orbiter's three fuel cells. Fuel cell No. 2 indicated higher than allowable temperatures during activation as countdown proceeded. The fuel cell was removed and replaced. Liftoff on September 7 was preceded by a smooth countdown.
Orbital Altitude & Inclination	165 nmi (306 km), 28.45 deg
Launch Weight (lb/kg)	256,645[a]/116,412
Landing & Postlanding Operations	September 18, 1995, 7:37:56 a.m. EDT, Runway 33, Kennedy Space Center. The landing occurred at the first opportunity.
Rollout Distance (ft/m)	10,230/3,118
Rollout Time (seconds)	56
Mission Duration	260 hr, 28 min, 26 sec
Landed Revolution No.	170
Mission Support	STDN
Primary Objective	Deployment and retrieval of SPARTAN 201-03 and WSF-2
Deployed Satellites	Deployed and retrieved SPARTAN 201-03 and WSF-2

Table 3–95. STS-69 Mission Characteristics (Continued)

Experiments	International Extreme Ultraviolet Hitchhiker-1 (IEH): The IEH consisted of a Hitchhiker carrier with four experiments: • Solar Extreme Ultraviolet Hitchhiker (SEH): The SEH was contained in an extended GAS canister with a Hitchhiker Motorized Door Assembly. The SEH used rare gas ionization cells, photodiodes, and a spectrometer for solar viewing. • Ultraviolet Spectrograph Telescope for Astronomical Research (UVSTAR): This was a spectrograph with internal gimbals, allowing for stellar observations. • GLO-3: This spectrograph measured Shuttle glow phenomena in the 115 nm to 1150 nm spectral range • CONCAP IV-03: See STS-57. STL/NIH-C: See STS-59. Electrolysis Performance Improvement Concept Study (EPICS): This study was a characterization in microgravity of the water electrolysis concepts to be used for metabolic oxygen generation in Space Station *Freedom* and other life support, propulsion, EVA, and space power applications. Commercial Materials Dispersion Apparatus (MDS) CMIX: See STS-56. CGBA Configuration A: See STS-54. BRIC Block 2: See STS-64.
Get Away Specials	Capillary Pumped Loop (CAPL)/Gas Bridge Assembly (GBA): The combined CAPL-2/GBA payload consisted of the CAPL-2 Hitchhiker payload, the TES-2 payload, four GAS payloads, and the Sample Return Experiment. CAPL-2: CAPL-2 was a reflight of the CAPL-1 Hitchhiker payload flown on STS-60 with modifications to enhance the startup of its capillary system. This flight verified the heat transport requirements of the thermal control system under design for the EOS. See STS-60. TES-2: The TES-2 was designed to provide data for understanding the long-duration behavior of TES fluoride salts that undergo repeated melting and freezing in microgravity. It developed a melt/freeze behavior database for TES phase change materials, leading to performance enhancements for solar-dynamic power system heat receivers.

Table 3–95. STS-69 Mission Characteristics (Continued)

Get Away Specials	G-645 Customer: Millcreek Township School District Investigation of Electroheological Fluids: This experiment investigated the performance of electroheological fluid-filled beams used as structural dampers in space.
	G-702 Customer: Lewis Research Center Microgravity Smoldering Combustion: This experiment increased the understanding of smoldering combustion in long-term microgravity.
	G-726 Customer: Langley Research Center Joint Damping Experiment: The experiment measured influence of gravity on the structural damping of a three-bay truss.
	G-515 Customer: ESA G-515 studied active damping control loops using a flexible plate and two piezo (pressure) actuators.
	Sample Return Experiment: The Sample Return Experiment sat on top the ballast GAS can. The primary science objective was the quantification of extraterrestrial particles and other orbital debris present in the orbiter bay. A secondary objective was a realistic test for comet sample collection concepts.
Mission Results	Successful
Remarks	This was the first time that two different payloads were retrieved and deployed during the same mission.

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[a] Jenkins, p. 303.

Table 3–96. STS-73 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Kenneth D. Bowersox PLT: Kent V. Rominger MS: Catherine G. Coleman, Michael E. Lopez-Alegria PC: Kathryn C. Thornton PS: Fred W. Leslie, Albert Sacco, Jr.
Launch	October 20, 1995, 9:53:00 a.m. EDT, Kennedy Space Center, Pad 39-B. The launch was after *Columbia*'s return to the fleet following its scheduled modification and refurbishment. A successful launch took place after six scrubs, which tied STS-61-C for the greatest number of launch scrubs. Liftoff originally set for September 25 was scrubbed shortly after tanking began, when a hydrogen leak was detected in the main engine No. 1 main fuel valve. The valve was replaced at the pad. The launch was reset for October 5, but Hurricane Opal led to an L-1 day decision to postpone launch one day to October 6. The October 6 launch attempt was scrubbed before external tank loading when it was determined that the hydraulic fluid had been inadvertently drained from hydraulic system 1 following the main engine No. 1 fuel valve replacement. A compressibility test demonstrated that the system was satisfactory for launch, and liftoff was reset to occur October 7. The launch attempt October 7 was scrubbed at T-20 seconds when master events controller 1 failed to operate properly and mission managers determined that it needed to be replaced. The launch was reset for October 14, and then rescheduled for October 15 to allow additional time to inspect the main engine oxidizer ducts because of crack in a test engine oxidizer duct found at Stennis Space Center. A launch attempt October 15 was postponed at T-5 minutes due to low clouds and rain. The launch was tentatively reset to October 19, pending a successful Atlas launch October 18. However, the Atlas launch was delayed, and STS-73 launch was moved to October 20. Countdown to liftoff on October 20 was delayed 3 minutes due to a range computer glitch.
Orbital Altitude & Inclination	150 nmi (277 km), 39.00 deg
Launch Weight (lb/kg)	257,017[a]/116,581
Landing & Postlanding Operations	November 5, 1995, 6:45:21 a.m. EST, Runway 33, Kennedy Space Center. The landing occurred on the first opportunity.

Table 3–96. STS-73 Mission Characteristics (Continued)

Rollout Distance (ft/m)	9,117/2,779
Rollout Time (seconds)	55
Mission Duration	381 hr, 52 min, 22, sec
Landed Revolution No.	255
Mission Support	STDN
Primary Objective	Research using the USML-2
Deployed Satellites	None
Experiments	USML-2: This was the second U.S. Spacelab mission dedicated to microgravity research. It consisted of 14 facilities performing 18 experiments and 7 investigations. The research was dedicated to fluid dynamics, crystal growth, combustion science, biological science, and technology demonstrations. Government, colleges, and private industry were involved in all facets of the research. • Primary experiments: – CGF – DPM – Geophysical Fluid Flow Cell (GFFC) – STDCE – GBX • Small Middeck Experiment Rack (SMIDEX) – APCF – LBNP – CGBA ASTROCULTURE™ facility and experiment The Glovebox-enclosed cabinet offered a clean working space and minimized contamination risks for these experiments: • Interface Configuration Experiment (ICE) • Oscillatory Thermocapillary Flow Experiment (OTFE) • Fiber Supported Droplet Combustion (FSDC) • Protein Crystal Growth–Glovebox (PCGG) • Zeolite Crystal Growth–Glovebox (ZCGG) • Colloidal Disorder-Order Transitions (CDOT) • Particle Dispersion Experiment (PDE) OARE: Provided near real-time data for characterizing the low frequency microgravity in the orbiter in support of USML-2. See STS-40.
Get Away Specials	None
Mission Results	Successful
Remarks	*Columbia* was outfitted with extended duration orbiter hardware for the flight.

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[a] Jenkins, p. 303.

Table 3–97. STS-74 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Kenneth D. Cameron PLT: James D. Halsell, Jr. MS: Chris A. Hadfield (CSA), Jerry L. Ross, William S. McArthur, Jr.
Launch	November 12, 1995, 7:30:43 a.m. EST, Kennedy Space Center, Pad 39-A. The planned rendezvous with *Mir* necessitated a brief launch window of about 7 minutes. Liftoff originally set for November 11, was scrubbed due to unacceptable weather at the TAL sites.[a] Countdown the following day proceeded smoothly to an on-time liftoff.
Orbital Altitude & Inclination	213 nmi (394 km), 51.60 deg
Launch Weight (lb/kg)	274,560[b]/124,538
Landing & Postlanding Operations	November 20, 1995, 12:01:27 p.m. EST, Runway 33, Kennedy Space Center
Rollout Distance (ft/m)	8,607/2,623
Rollout Time (seconds)	57
Mission Duration	196 hr, 30 min, 46 sec
Landed Revolution No.	128
Mission Support	STDN
Primary Objective	Second Shuttle-*Mir* docking
Deployed Satellites	None
Experiments	ICBC: A 65-mm color camera mounted in the payload bay documented DM installation, the *Mir* rendezvous, docking, flyaround, and separation. GLO Experiment/Photogrammetric Appendage Structural Dynamics Experiment (PASDE) Payload (GPP): The GLO experiment obtained data from the Shuttle and *Mir* glow emissions for various conditions. Three PASDE canisters, located throughout the cargo bay, photogrammetrically recorded structural response data of the *Mir* solar arrays during the docked phase of the mission. SAREX-II: See STS-35.
Get Away Specials	None
Mission Results	Successful

Table 3–97. STS-74 Mission Characteristics (Continued)

Remarks	Shuttle-*Mir* Mission 2 (S/MM-2): This mission delivered the Russian-built DM with two solar arrays attached. The DM was installed on the ODS to be docked to the *Mir* Kristall module. The DM remained attached the *Mir* to provide for future Shuttle and Soyuz-TM dockings. The port solar array was a Russian-built Reusable Solar Array (RSA) while Lewis Research Center built the starboard Cooperative Solar Array (CSA). The crews retrieved and resupplied microgravity and life science experiments on board *Mir*, performed ISS Risk Mitigation Experiments (RME), and resupplied *Mir*.

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[a] NASA used the term "transoceanic abort landing" in Section 6.4 of the 1997 *Shuttle Flight Operations Manual* rather than "transatlantic landing," which it used in the 1988 *NSTS Shuttle Reference Manual*. Although some references to the older abort term continued to appear in mission documents, the Mission Chronology for STS-74 in 1995 specifically used "transoceanic abort landing" in its mission description. See "Space Station Mission Chronology: STS-74," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-74.htm* (accessed November 28, 2005); E-mail from Kyle Herring, November 30, 2005.

[b] Jenkins, p. 303.

Table 3–98. STS-72 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Brian Duffy PLT: Brent W. Jett, Jr. MS: Leroy Chiao, Winston E. Scott, Koichi Wakata (JAXA), Daniel T. Barry
Launch	January 11, 1996, 4:41:00 a.m. EST, Kennedy Space Center, Pad 39-B. The countdown to the first Shuttle launch of the year proceeded smoothly except for a 23-minute delay due to communication glitches between various sites on the ground and to reduce the risk of colliding with space debris.
Orbital Altitude & Inclination	250 nmi (463 km), 28.45 deg
Launch Weight (lb/kg)	258,391[a]/117,204
Landing & Postlanding Operations	January 20, 1996, 2:41:41 a.m. EST, Runway 15, Kennedy Space Center. *Endeavour* landed on its first opportunity.
Rollout Distance (ft/m)	8,770/2,673
Rollout Time (seconds)	66
Mission Duration	218 hr, 0 min, 45 sec
Landed Revolution No.	142
Mission Support	STDN
Primary Objective	Deployment and retrieval of SPARTAN OAST-Flyer; retrieval of Space Flyer Unit
Deployed Satellites	Deployed and retrieved SPARTAN OAST-Flyer Retrieved Japanese Space Flyer Unit
Experiments	SSBUV-A: See STS-34. PARE/NIH-R-03: See STS-66. STL/NIH-C-05: See STS-59. PCG-STES-04: See STS-63. CPCG-08: See STS-49. EDFT-03: This test evaluated and demonstrated mission-critical EVA hardware for its planned use to support the scheduled EVAs for the Space Station. Shuttle Laser Altimeter-01: This experiment was the first of four planned remote sensing flights to precisely measure the distance between Earth's surface and the Space Shuttle. The experiment acquired samples of land topology and vegetation data to demonstrate laser altimeter operation in low Earth orbit and measure cloud top height, structure, and aerosol layering. The experiment also provided an in-space engineering testbed for future spaceflight laser sensors.

Table 3–98. STS-72 Mission Characteristics (Continued)

Get Away Specials	G-342 Customer: U.S. Air Force, Space and Missile Systems Center Flexible Beam Experiment 2 (FLEXBEAM 2): The FLEXBEAM 2 investigated vibrations in space by exciting two Aluminum 6061 T-6 cantilevered beams. Each beam was subjected to different initial conditions resulting in exciting different modes. Electromagnetic sensors measured the vibrations while a recorder stored the data. G-459 Customer: Society of Japanese Aerospace Co.'s, Inc. (SJAC) PCG This experiment reexamined the effect of the microgravity environment on protein-crystal nucleation. Crystal form and size were recorded on photographic film and analyzed after recovery of the payload. To adapt to a GAS payload canister, researchers developed a hardware system using 16 independent crystallization units. Each of the units could carry out crystallization experiments by one of three crystallization methods, i.e., batch, vapor diffusion, and free-interface diffusion. G-740 Customer: Lewis Research Center Pool Boiling Experiment: This experiment was an extension of the study of the fundamentals of nucleate pool boiling heat transfer under the microgravity conditions of space. An improved understanding of the basic processes that constitute boiling was sought by removing the buoyancy effects that mask other phenomena.
Mission Results	Successful
Remarks	Two EVAs were conducted as part of the continuing series to prepare for on-orbit construction of the ISS. During the first EVA, lasting 6 hours, 9 minutes, Chiao and Barry evaluated a new portable work platform and a structure known as the rigid umbilical, which might eventually be used to hold various fluid and electrical lines. During the second EVA, conducted by Chiao and Scott, lasting 6 hours, 53 minutes, a portable work platform was again evaluated. Also tested were a Space Station utility box designed to hold avionics and fluid line connects. Scott also tested a spacesuit's thermal control in severe cold up to -104°F (-75°C).

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[a] Jenkins, p. 303.

Table 3–99. STS-75 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Andrew M. Allen PLT: Scott J. Horowitz MS: Jeffrey A. Hoffman, Maurizio Cheli (ESA), Claude Nicollier (ESA) PC: Franklin R. Chang-Diaz PS: Umberto Guidoni (ESA)
Launch	February 22, 1996, 3:18:00 p.m. EST, Kennedy Space Center, Pad 39-B. The liftoff occurred on-time following a smooth countdown. Six seconds after liftoff, the crew reported that the left main engine chamber pressure meter was showing only 40 percent thrust instead of 104 percent thrust that was necessary prior to throttle-down. Mission controllers in Houston reported that telemetry showed all three engines were performing nominally, and there was no effect on the ascent phase.
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	261,927[a]/118,808
Landing & Postlanding Operations	March 9, 1996, 8:58:21 a.m. EST, Runway 33, Kennedy Space Center. A March 8 landing was waved off due to unfavorable weather conditions.
Rollout Distance (ft/m)	8,459/2,578
Rollout Time (seconds)	64
Mission Duration	377 hr, 40 min, 21 sec
Landed Revolution No.	251
Mission Support	STDN
Primary Objective	Flight of TSS-1R; experimentation using USMP-3
Deployed Satellites	U.S./Italian TSS-1R—The satellite was lost during the mission (see Remarks below).
Experiments	USMP-3: The crew performed microgravity research to advance understanding of materials science and condensed matter physics. • Supporting hardware included: – SAMS – OARE • USMP-3 experiments were: – AADSF – ZENO – IDGE – MEPHISTO

Table 3–99. STS-75 Mission Characteristics (Continued)

Experiments	Middeck Glovebox Facility (MGBX): This facility provided a safe laboratory workbench for three combustion experiments: • Forced-Flow Flamespreading Test (FFFT) • Radiative Ignition and Transition to Spread Investigation (RITSI) • Comparative Soot Diagnostics (CSD) CPCG: See STS-49.
Get Away Specials	None
Mission Results	The tether snapped on flight day three as TSS-1R was just short of full deployment at about 12.8 mi (20.6 km). The satellite immediately began speeding away from the orbiter because of orbital forces; the crew was never in danger. Other mission objectives were successfully achieved.

[a] Jenkins, p. 303.

Table 3–100. STS-76 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Kevin P. Chilton PLT: Richard A. Searfoss MS: Ronald M. Sega, Michael R. Clifford, Linda M. Godwin, Shannon W. Lucid (remained on *Mir*)
Launch	March 22, 1996, 3:13:04 a.m. EST, Kennedy Space Center, Pad 39-B. The first launch attempt set for March 21 was scrubbed before beginning tanking operations March 20 due to concerns about high winds. The launch reset for March 22 proceeded smoothly to an on-time liftoff. During ascent, a leak occurred in the hydraulic system powered by APU No. 3. The leak stopped after hydraulic system shutdown on orbit. Mission managers concluded that the system would remain stable and proceeded with plans for a full-duration mission.
Orbital Altitude & Inclination	160 nmi (296 km), 51.60 deg
Launch Weight (lb/kg)	246,337[a]/111,737
Landing & Postlanding Operations	March 31, 1996, 5:28:57 a.m. PST, Runway 22, Edwards Air Force Base. Mission managers rescheduled the landing from March 31 to March 30 in anticipation of rain and clouds at the Kennedy Space Center landing site, but landing attempts at Kennedy Space Center on both March 30 and March 31 were waved off due to weather. The orbiter was finally diverted to California. More conservative weather criteria were employed for landing due to the leak in the APU No. 3 hydraulic system and special measures were taken during reentry to minimize use of this APU. During landing preparations, 3 of 38 reaction control system thrusters failed, but backup thrusters were available to perform the same functions. It was not considered a night landing because landing occurred 11 minutes before sunrise. Flight rules define night launch/landing as one occurring at least 15 minutes after sunset and at least 15 minutes before sunrise.
Rollout Distance (ft/m)	8,357/2,547
Rollout Time (seconds)	55
Mission Duration	221 hr, 15 min, 33 sec
Landed Revolution No.	145
Mission Support	STDN
Primary Objective	Third Shuttle-*Mir* docking; research and transfer of supplies using SPACEHAB-Single Module
Deployed Satellites	None

Table 3–100. STS-76 Mission Characteristics (Continued)

Experiments	SPACEHAB-SM: A single module configuration carried a mix of supplies and scientific equipment to and from *Mir*. • Equipment in this module: – Russian logistics – EVA tools – ISS Risk Mitigation Experiment – American logistics – Science and technology experiments • RME: – *Mir* Electric Field Characterization (MEFC) hardware – *Mir* Environmental Effects Payload (MEEP) • Science and Technology Experiments: – ESA's Biorack – Life Sciences Laboratory Equipment Refrigerator/Freezer (LSLE R/F) – *Mir* Glovebox Stowage – QUELD – High Temperature Liquid Phase Sintering (LPS) • *Mir* Environmental Effects Payload (MEEP): – Polished Plate Micrometeoroid Debris (PPMD) experiment – Orbital Debris Collector (ODC) experiment – Passive Optical Samples (POSA) I and II • *Mir* Glovebox Stowage: – Combustion Experiments Parts Box – FFFT – Passive Accelerometer – PCG – PCG-TES Ancillary Kidsat: This project gave middle school students the opportunity to participate in space exploration by configuring their own payload of digital video and a camera for flight on the Shuttle. They could command the camera from their classrooms and download their images of Earth in near real-time. SAREX: See STS-35.
Get Away Specials	G-312 Customer: U.S. Air Force Space Test Program Naval Research Laboratory's Trapped Ions In Space (TRIS) Experiment: This experiment measured a recently discovered belt of energetic cosmic ray nuclei trapped in Earth's magnetic field to quantify radiation hazards in space to develop a better theoretical understanding of how these cosmic ray nuclei became trapped in Earth's magnetic field. TRIS flew previously on a Space Shuttle mission in 1984.
Mission Results	Successful

Table 3–100. STS-76 Mission Characteristics (Continued)

Remarks	During this Shuttle-*Mir* docking, astronauts Linda Godwin and Michael Clifford conducted the first U.S. EVA around two mated spacecraft. During the 6-hour, 2-minute EVA, they attached four MEEP experiments to *Mir*'s DM that would characterize the environment around *Mir* over an 18-month period. The two wore SAFER propulsive devices.

[a] Jenkins, p. 310.

Table 3–101. STS-77 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: John H. Casper PLT: Curtis L. Brown, Jr. MS: Andrew S.W. Thomas, Daniel W. Bursch, Mario Runco, Jr., Marc Garneau (CSA)
Launch	May 19, 1996, 6:30:00 a.m. EDT, Kennedy Space Center, Pad 39-B. The original launch date of May 16 was changed to May 19 due to Eastern Range schedule conflicts. The countdown proceeded smoothly to an on-time liftoff on May 19.
Orbital Altitude & Inclination	153 nmi (283 km), 39.00 deg
Launch Weight (lb/kg)	254,891[a]/115,617
Landing & Postlanding Operations	May 29, 1996, 7:09:18 a.m. EDT, Runway 33, Kennedy Space Center. Favorable weather allowed for a landing at the first opportunity.
Rollout Distance (ft/m)	9,291/2,832
Rollout Time (seconds)	42
Mission Duration	240 hr, 39 min, 24 sec
Landed Revolution No.	160
Mission Support	STDN
Primary Objective	Deployment and retrieval of SPARTAN 207 IAE; experimentation using SPACEHAB-04 and TEAMS
Deployed Satellites	Deployed and retrieved SPARTAN 207 carrying the IAE. The PAMS and Satellite Test Unit (STU) were deployed but not retrieved; however, *Endeavour* did rendezvous three times with the satellite.
Experiments	SPACEHAB 04: This mission carried 12 experiments primarily involved in the materials and life sciences. • Advanced Separations (ADSEP) • Commercial Float Zone Furnace (CFZF) • CGBA • Commercial Vapor Diffusion Apparatus (CVDA) • FGBA • Hand Held-Diffusion Test Cells (HH-DTC) • IMMUNE • PCF • Protein Crystal Facility-Light Scattering and Temperature Controlled (PCF-LST) • Plant Growth Bioprocessing Apparatus (PGBA) • Space Experiment Facility (SEF) • GPPM

Table 3–101. STS-77 Mission Characteristics (Continued)

Experiments	TEAMS: Hitchhiker carrier had four experiments: • GPS Attitude and Navigation Experiment (GANE) • Vented Tank Resupply Experiment (VTRE) • Liquid Metal Thermal Experiment (LMTE) • PAMS
	Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE): This experiment tested advanced sorption cooler techniques using hydrogen as a coolant.
	Aquatic Research Facility-01 (ARF-01): This facility supported life science research using a broad range of small aquatic species.
	BRIC-07: See STS-64.
	TPCE/RFL: This experiment obtained data required to develop the technology for pressure control of cryogenic tankage.
Get Away Specials	G-056 Customer: California Institute of Technology, Pasadena, California Gamma-ray Astrophysics Mission (GAMCIT): The GAMCIT studied gamma-ray bursts, an enigmatic source of cosmic radiation.
	G-142 and G-144 Customer: DARA Heat Transfer Phenomena (G-142) and Reaction Kinetics in Glass Melts (G-144): Autonomous Material Science Experiments Under Microgravity (MAUS): Germany offered scientists from disciplines of material research and processing the opportunity to perform material science investigations under microgravity conditions.
	G-063 Customer: Pennsylvania State University G-063 gave students first-hand experience at designing a self-contained space experiment. Once the payload returned from its flight, the students observed its results. The experiments included an accelerometer to measure the impact of orbital debris and a magnetometer to measure the magnetic fields. There was also an experiment to test the effect of a single event upset due to effects of cosmic radiation on semiconductors.
	G-163 Customer: Johnson Space Center Diffusion Coefficient Measurement Facility (DCMF): This facility measured the speed at which mercuric iodide (solid) evaporated and then was transported as a vapor under microgravity conditions.

Table 3–101. STS-77 Mission Characteristics (Continued)

Get Away Specials	G-200 Customer: Utah State University Three experiments were flown in the canister. The payload also contained popcorn kernels in ziplock bags as part of an experiment by elementary school students. After return to Earth, students popped the popcorn and compared it to a similar sample maintained in Earth's gravity.
	G-490 Customer: British Sugar PLC The experiment was designed and constructed by the School of Electronics and Electrical Engineering at the Robert Gordon University, Aberdeen, Scotland. British Sugar PLC sponsored the launch services. The first experiment was to verify a proposal that a low-level gravitational field could be measured by observing its effect on the convection currents present in a heated liquid. The second project was devised by a group of children from Elrick Primary School near Aberdeen, Scotland. A series of controlled experiments were carried out on selected samples of seeds, oats, wheat, barley, and nape-oil to quantify the effects of spaceflight on growth patterns.
	G-564 and G-565 Customer: CSA Nanocrystal Get Away Special (NANO-GAS) and Atlantic Canada Thin Organic Semiconductors (ACTORS): The results of these experiments contributed to the development of new materials with applications in high-performance laser, electronic equipment, and components.
	G-703 Customer: Lewis Research Center Microgravity Smoldering Combustion (MSC): This experiment studied the smolder characteristics of porous combustible materials in a microgravity environment.
	G-741 Customer: Lewis Research Center Pool Boiling Experiment: This experiment was an extension of the study of the fundamentals of nucleate pool boiling heat transfer under the microgravity conditions of space.
Mission Results	Successful

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[a] Jenkins, p. 310.

Table 3–102. STS-78 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Terence T. Henricks PLT: Kevin R. Kregel MS: Richard M. Linnehan, Charles E. Brady, Jr. PC: Susan J. Helms PS: Jean-Jacques Favier (CNES), Robert Brent Thirsk (CSA)
Launch	June 20, 1996, 10:49:00 a.m. EDT, Kennedy Space Center, Pad 39-B. The liftoff proceeded on time. An in-cabin camera provided the first video images from the flight deck, beginning with crew ingress and continuing through main engine cutoff. Postlaunch assessment of spent solid rocket boosters revealed a hot gas path in motor field joints to, not past, the capture feature O-ring. This marked the first occurrence of combustion product penetration into the J-joint of the redesigned solid rocket motor. Flight safety was not compromised, and motor performance met design specification requirements. The probable cause was a new, more environmentally friendly adhesive and cleaning fluid.
Orbital Altitude & Inclination	150 nmi (278 km), 39.00 deg
Launch Weight (lb/kg)	256,145[a]/116,185
Landing & Postlanding Operations	July 7, 1996, 8:36:45 a.m. EDT, Runway 33, Kennedy Space Center. This mission had the first live downlink video during an orbiter's descent. After landing, Henricks and Kregel participated in the Olympic Torch Ceremony at Kennedy Space Center Visitors Center.
Rollout Distance (ft/m)	9,339/2,847
Rollout Time (seconds)	45
Mission Duration	405 hr, 47 min, 36 sec
Landed Revolution No.	271
Mission Support	STDN
Primary Objective	Experimentation using the LMS
Deployed Satellites	None

Table 3–102. STS-78 Mission Characteristics (Continued)

Experiments	LMS using the Spacelab long module: Five space agencies represented a complement of multinational experiments representing microgravity science and applications with emphasis on material and life science processing. These space agencies were: NASA, ESA, the French Space Agency, CSA, and the Italian Space Agency. Research scientists from 10 countries worked together on this payload, which made use of the Spacelab long module. • Human Physiology Experiments: Musculoskeletal Investigations – Effects of Weightlessness on Human Single Muscle Fiber Function – Relationship of Long-Term Electromyographic Activity and Hormonal Function to Muscle Atrophy and Performance – Effects of Microgravity on Skeletal Muscle Contractile Properties – Effects of Microgravity on the Biomechanical and Bioenergetic Characteristics of Human Skeletal Muscle – Magnetic Resonance Imaging After Exposure to Microgravity (Ground Study) – An Approach to Counteract Impairment of Musculoskeletal Function in Space (Ground Study) • Human Physiology Experiments: Metabolic Investigations – Direct Measurement of the Initial Bone Response to Spaceflight in Humans – Measurement of Energy Expenditures During Spaceflight Using the Doubly Labeled Water Method • Human Physiology Experiments: Pulmonary Investigations – Extended Studies of Pulmonary Function in Weightlessness • Human Physiology Experiments: Human Behavior and Performance Investigations – Human Sleep, Circadian Rhythms, and Performance in Space – Microgravity Effects on Standardized Cognitive Performance Measures • Human Physiology Experiments: Neuroscience Investigations – Torso Rotation Experiment – Canal and Otolith Integration Studies (COIS)

Table 3–102. STS-78 Mission Characteristics (Continued)

Experiments	• Microgravity Science: BDPU – Bubbles and Drop Interaction with Solidification Front – Boiling on Small Plate Heaters Under Microgravity and a Comparison with Earth Gravity – A Liquid Electrohydrodynamics Experiment – Thermocapillary Convection in Multilayer Systems – Nonlinear Surface Tension-Driven Bubble Migration – Oscillatory Thermocapillary Instability – Thermocapillary Migration and Interactions of Bubbles and Drops • Microgravity Science: Advanced Gradient Heating Facility (AGHF)–Materials Processing – Directional Solidification of Refined Al–4 wt. % Cu Alloys – Coupled Growth in Hypermonotectics – Effects of Convection on Interface Curvature During Growth of Concentrated Tenary Compounds – Directional Solidification of Refined Al–1.5 wt.% Ni Alloys – Interactive Response of Advancing Phase Boundaries to Particles – Particle Engulfment and Pushing by Solidifying Interfaces • Microgravity Science: APCF–Medical Research – Crystallization of EGFR-EGF – Crystallization of Apocrustacyanin Cl – Crystallization and X-ray Analysis of 5S rRNA and the 5S rRNA Domain A – Growth of Lysozyme Crystals at Low Nucleation Density – Comparative Analysis of Aspartyl tRA-Synthetase and Thaumatin Crystals Grown on Earth and in Microgravity – Crystallization of the Nucleosome Core Particle – Crystallization of Photosystem I – Mechanism of Membrane Protein Crystal Growth: Bacteriorhodopsin-Mixed Micelle Packing at the Consolution Boundary, Stabilized in Microgravity – Crystallization in a Microgravity Environment of CcdB, a Protein Involved in the Control of Cell Death – Crystallization of Sulfolobus Solfataricus – Lysosome Crystal Growth in the Advanced Protein Crystallization Facility Monitored via Mach-Zehdner Interferometry and CCD Video – Analysis of Thaumatin Crystals Grown on Earth and in Microgravity

Table 3–102. STS-78 Mission Characteristics (Continued)

Experiments	• Microgravity Science: Accelerometers–Characterizing the Microgravity Environment – OARE – Microgravity Measurement Assembly (MMA) – SAMS • Space Biology: – Compression Wood Formation in a Microgravity Environment – Development of the Fish Medaka in Microgravity – Role of Corticosteroids in Bone Loss During Spaceflight SAREX-II: See STS-35. BRIC-07: See STS-64.
Get Away Specials	None
Mission Results	Successful
Remarks	*Columbia* was outfitted with Extended Duration Orbiter hardware for this mission.

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[a] Jenkins, p. 310.

Table 3–103. STS-79 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: William F. Readdy PLT: Terence W. Wilcutt MS: Jerome Apt, Thomas D. Akers, Carl E. Walz, John E. Blaha (remained on *Mir*), Shannon W. Lucid (departed *Mir* for return to Earth)
Launch	September 16, 1996, 4:54:49 a.m. EDT, Kennedy Space Center, Pad 39-A. The launch, originally set for July 31, slipped when mission managers decided to switch out *Atlantis*'s twin solid rocket boosters. The new launch date of September 12 was targeted and *Atlantis* returned to the launch pad. The launch date was delayed to September 16 when the Shuttle was returned to the VAB due to the threat from Hurricane Fran. The countdown proceeded smoothly to an on-time liftoff September 16. Approximately 13 minutes into flight, auxiliary power unit No. 2 shut down prematurely. After review and analysis, the Mission Management Team concluded the mission could proceed to its nominal end-of-mission as planned.
Orbital Altitude & Inclination	170-213 nmi (315-394 km), 51.60 deg
Launch Weight (lb/kg)	249,328[a]/113,093
Landing & Postlanding Operations	September 26, 1996, 8:13:15 a.m. EDT, Runway 15, Kennedy Space Center. The landing went smoothly at first opportunity.
Rollout Distance (ft/m)	10,981/3,347
Rollout Time (seconds)	62
Mission Duration	243 hr, 18 min, 24 sec
Landed Revolution No.	159
Mission Support	STDN
Primary Objective	S/MM-04; experimentation using SPACEHAB-05
Deployed Satellites	None

Table 3–103. STS-79 Mission Characteristics (Continued)

Experiments	SPACEHAB-05: A double SPACEHAB module carried experiments in its forward portion that were conducted by the crew before, during, and after *Atlantis*'s docking to *Mir*. The aft portion of the module housed primarily the logistics equipment to be transferred to *Mir*. • Experiments returning from *Mir*: – Environmental Radiation Measurements – Greenhouse-Integrated Plant Experiments – Human Life Sciences – Assessment of Humoral Immune Function During Long Duration Space Flight • Experiments remaining on *Mir* for later retrieval: – BTS – MIDAS – CGBA • Roundtrip experiments on *Atlantis*: – Extreme Temperature Translation Furnace (ETTF) – CPCG experiments – Mechanics of Granular Materials (MGM) • Risk Mitigation Experiments: – Mated Shuttle and *Mir* Structural Dynamics Test (1301) – *Mir* Electric Field Characterization (1302) – Shuttle/*Mir* Experiment Kit Transport (1303) – Shuttle/*Mir* Alignment Stability Experiment (1310) – Real-Time Radiation Monitoring Device (RRMD: 1312) – Active Rack Isolation System (ARIS: 1313) – Inventory Management System (1319)
	IMAX: Large format motion picture system photographed *Mir* during undocking and flyaround. The crews also used the camera to photograph *Mir* interior scenes.
	Midcourse Space Experiment (MSX): The MSX obtained ultraviolet, infrared, and visible data of the Shuttle and Shuttle thrusters from an independent, space-based sensor satellite in a 99-degree orbit.
	SAREX-II: See STS-35.
Get Away Specials	None
Mission Results	Successful

[a] Jenkins, p. 310.

Table 3–104. STS-80 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Kenneth D. Cockrell PLT: Kent V. Rominger PC: Tamara E. Jernigan MS: Thomas D. Jones, F. Story Musgrave
Launch	November 19, 1996, 2:55:47 p.m. EST, Kennedy Space Center, Pad 39-B. Launch date of October 31 was first threatened by the changeout of the STS-79 boosters with those slated to fly on STS-80 and the delay of the STS-79 liftoff. Hurricane preparations because of Hurricane Fran in early September halted the STS-80 booster stacking operations in the VAB, prompting mission managers to reschedule the launch date to November 8. At the Flight Readiness Review (FRR) on October 28, mission managers declined to formalize the launch date pending an analysis of erosion in the STS-79 booster nozzles. At the FRR on November 4, the launch date was changed to no earlier than November 15 to allow engineers more time to complete their study of nozzle erosion. At the follow-up FRR on November 11, November 15 was set as the official launch date, pending a commercial Atlas launch on November 13, and the launch count began. The launch was postponed to November 19, due to the scrub of the Atlas launch and predicted bad weather in the Kennedy Space Center vicinity for a period of several days, and the count remained in an extended hold. The launch on November 19 occurred about 3 minutes after the scheduled opening of the launch window due to a hold at T-31 seconds to assess hydrogen concentrations in the aft engine compartment.
Orbital Altitude & Inclination	189 nmi (350 km), 28.45 deg
Launch Weight (lb/kg)	260,935[a]/118,358
Landing & Postlanding Operations	December 7, 1996, 6:49:05 a.m. EST, Runway 33, Kennedy Space Center. Landing was originally scheduled for December 5, but *Columbia* was waved off two days in a row due to weather conditions in Florida.
Rollout Distance (ft/m)	8,721/2,658
Rollout Time (seconds)	62
Mission Duration	423 hr, 53 min, 19 sec
Landed Revolution No.	277
Mission Support	STDN

Table 3–104. STS-80 Mission Characteristics (Continued)

Primary Objective	Deployment and retrieval of ORFEUS-SPAS-2 and WSF-3
Deployed Satellites	Deployed and retrieved ORFEUS-SPAS-2 and WSF-3
Experiments	NIH-R4: This experiment studied blood pressure regulation and function in rats fed either a high-calcium or a low-calcium diet before and during spaceflight. CCM-A (formerly STL/NIH-C-05): This experiment continued the investigation into how microgravity affected bones at the cellular level. BRIC-09: See STS-64. CMIX-5: See STS-52. Visualization in an Experimental Water Capillary Pumped Loop (VIEW-CPL): This experiment collected and transported excess heat generated by spacecraft instruments to a spacecraft radiator for ejection into space. The experiment was used to develop a more complete understanding of CPL physics in a microgravity environment by viewing the fluid flow inside the evaporator.
Get Away Specials	None
SEM	SEM-01 experiments were: • Charleston, South Carolina, school district (CAN-DO): – Gravity and Acceleration Readings – Bacteria-Agar Research Instrument – Crystal Research in Space – Magnetic Attraction Viewed in Space • Purdue University, West Lafayette, Indiana: – Fluid Thermal Convection – NADH Oxidase Absorbance in Shrimp – Passive Particle Detector Experiment • Hampton Elementary School, Lutherville, Maryland: – Experimented with seeds; soil; chalk; crayon; calcite; Silly Putty; bubble solution; popcorn; mosquito eggs; and other organic compounds • Glenbrook North High School, Northbrook, Illinois: – Surface Tension Experiment • Albion Jr. High, Strongville, Ohio: – Heat Transfer Experiment–studied heating properties of copper tubes and pennies • Poquoson Middle School, Poquoson, Virginia: – Bacteria Inoculation in Space Experiment • Norfolk Public Schools Science and Technology Advanced Research (NORSTAR): – Observed the behavior of immiscible fluids

Table 3–104. STS-80 Mission Characteristics (Continued)

Mission Results	Two EVAs by Jernigan and Jones planned to evaluate equipment and procedures to be used during construction and maintenance of the ISS were canceled because the crew could not open the outer airlock hatch. Crew and mission troubleshooting did not reveal the cause, so mission managers concluded it would be unwise to attempt the two EVAs and risk unnecessary damage to the hatch or seals. Postlanding assessment of the hatch indicated that a small screw had become loose from an internal assembly and lodged in an actuator, a gearbox mechanism that operated linkages securing the hatch, preventing the crew from opening the hatch. Other mission objectives were achieved.
Remarks	At age 61, Musgrave became the oldest human to fly in space. He set a new record for the most Shuttle flights (six) and tied astronaut John Young's record for the most total spaceflights.

[a] Jenkins, p. 310.

Table 3–105. STS-81 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Michael A. Baker PLT: Brent W. Jett, Jr. MS: Peter J.K. Wisoff, John M. Grunsfeld, Marsha S. Ivins, Jerry M. Linenger (remained on *Mir*), John E. Blaha (departed *Mir* for return to Earth)
Launch	January 12, 1997, 4:27:23 a.m. EST, Kennedy Space Center, Pad 39-B. The liftoff occurred on time following a smooth countdown.
Orbital Altitude & Inclination	160 nmi (296 km), 51.60 deg
Launch Weight (lb/kg)	249,936[a]/113,369
Landing & Postlanding Operations	January 22, 1997, 9:22:44 a.m. EST, Runway 33, Kennedy Space Center. The first landing opportunity was waved off due to weather.
Rollout Distance (ft/m)	9,350/2,850
Rollout Time (seconds)	69
Mission Duration	244 hr, 55 min, 23 sec
Landed Revolution No.	160
Mission Support	STDN
Primary Objective	S/MM-05; experimentation using SPACEHAB Double Module
Deployed Satellites	None
Experiments	SPACEHAB Double Module: The double module carried the following experiments: • Environmental Radiation Measurements • Greenhouse-Integrated Plant Experiments • Human Life Sciences • Assessment of Humoral Immune Function During Long Duration Space Flight • Diffusion-Controlled Crystallization Apparatus for Microgravity • Gaseous Nitrogen Dewar • Liquid Metal Diffusion • Optical Properties Monitor CREAM: See STS-48. KidSat: Provided students access to real-time images of Earth by uplinking commands to the Electronic Still Camera to photograph specific land areas. The images were downlinked in real time via the Ku-band Communication Adapter.

Table 3–105. STS-81 Mission Characteristics (Continued)

Experiments	SAMS: The SAMS provided acceleration data to characterize the experiments acceleration environment on *Mir*. See STS-43. MSX: The objective of the MSX was to fire the orbiter thrusters (orbital maneuvering and primary reaction control systems) in space and use the sophisticated sensors of the orbiting MSX satellite to collect ultraviolet, infrared, and visible light data of the event.
Get Away Specials	None
Mission Results	Successful
Remarks	This mission was the largest transfer to date of logistics between the two spacecraft.

[a] Jenkins, p. 310.

Table 3–106. STS-82 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Kenneth D. Bowersox PLT: Scott J. Horowitz MS: Joseph R. Tanner, Steven A. Hawley, Gregory J. Harbaugh, Steven L. Smith PC: Mark C. Lee
Launch	February 11, 1997, 3:55:17 a.m. EST, Kennedy Space Center, Pad 39-A. The launch originally targeted for February 13 was moved up to February 11 to provide more range opportunities. Countdown proceeded smoothly to an on-time liftoff on February 11. This was the first flight after *Discovery*'s OMDP.
Orbital Altitude & Inclination	313 nmi (579 km), 28.45 deg
Launch Weight (lb/kg)	251,238[a]/113,960
Landing & Postlanding Operations	February 21, 1997, 3:32:26 a.m. EST, Runway 15, Kennedy Space Center. The orbiter landed on the second opportunity after the first was waved off due to low clouds.
Rollout Distance (ft/m)	7,066/2,154
Rollout Time (seconds)	60
Mission Duration	239 hr, 37 min, 7 sec
Landed Revolution No.	149
Mission Support	STDN
Primary Objective	Second Hubble Space Telescope Servicing Mission
Deployed Satellites	Retrieved, serviced, and redeployed the Hubble Space Telescope
Experiments	MSX: See STS-81.
Get Away Specials	None
Mission Results	Successful
Remarks	There were five EVAs: four scheduled and one unscheduled. EVA No. 1: Performed by Lee and Smith, the first EVA lasted 6 hours, 42 minutes. Lee and Smith removed the GHRS and FOS from the telescope and replaced them with the STIS and NICMOS.

Table 3–106. STS-82 Mission Characteristics (Continued)

Remarks	EVA No. 2: Performed by Harbaugh and Tanner, the second EVA lasted 7 hours, 27 minutes. Harbaugh and Tanner replaced a degraded fine guidance sensor and a failed Engineering and Science Tape Recorder with new spares. They also installed a new unit called the Optical Control Electronics Enhancement Kit, which increased the capability of the fine guidance sensor. The astronauts noted cracking and wear on thermal insulation on the side of the telescope facing the Sun and in the direction of travel. EVA No. 3: Performed by Lee and Smith, the third EVA lasted 7 hours, 11 minutes. Lee and Smith removed and replaced a Data Interface Unit on the Hubble Space Telescope as well as an old reel-to-reel Engineering and Science Tape Recorder with a new digital solid state recorder (SSR) that allowed simultaneous recording and playback of data. The astronauts also changed out one of four reaction wheel assembly units that used spin momentum to move the telescope toward a target and maintain it in a stable position. EVA No. 4: Performed by Harbaugh and Tanner, the fourth EVA lasted 6 hours, 34 minutes. Harbaugh and Tanner replaced a solar array drive electronics package, which controlled the positioning of the Hubble Space Telescope's solar arrays. The astronauts also replaced covers over the telescope's magnetometers and placed thermal blankets of multilayer material over two areas of degraded insulation around the light shield portion of the telescope just below the top of the observatory. EVA No. 5: Performed by Lee and Smith, the fifth EVA lasted 5 hours, 17 minutes. Lee and Smith attached several thermal insulation blankets to three equipment compartments at the top of the Support Systems Module section of the telescope that contained key data processing, electronics, and scientific instrument telemetry packages.

[a] Jenkins, p. 310.

Table 3–107. STS-83 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: James D. Halsell, Jr. PLT: Susan L. Still PC: Janice E. Voss MS: Michael L. Gernhardt, Donald A. Thomas PS: Roger K. Crouch, Gregory T. Linteris
Launch	April 4, 1997, 2:20:32 p.m. EST, Kennedy Space Center, Pad 39-A. The launch originally was set for April 3. It was initially delayed 24 hours on April 1 due to a requirement to add additional thermal insulation to a water coolant line in the orbiter's payload bay. Mission managers determined that the coolant line, which cooled various electronics on the orbiter, was not properly insulated and could possibly freeze on-orbit. On April 4, liftoff was delayed 20 minutes, 32 seconds due to an orbiter access hatch seal that had to be replaced.
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	259,144[a]/117,546
Landing & Postlanding Operations	April 8, 1997, 2:33:11 p.m. EDT, Runway 33, Kennedy Space Center. The landing was originally scheduled for April 19, but the mission was cut short due to problems with *Columbia*'s fuel cell No. 2.
Rollout Distance (ft/m)	8,602/2,622
Rollout Time (seconds)	59
Mission Duration	95 hr, 12 min, 39 sec
Landed Revolution No.	63
Mission Support	STDN
Primary Objective	Research using the MSL-1
Deployed Satellites	None
Experiments	MSL-1: The MSL-1 housed a collection of microgravity experiments inside a Spacelab long module. The laboratory featured facilities for material science investigations. Due to an early return because of problems with fuel cell No. 2, only a few experiments were conducted. • TEMPUS: – Thermophysical Properties of Undercooled Metallic Melts • Large Isothermal Furnace: – Liquid-Phase Sintering II • Combustion Module-1 (CM-1): – Laminar Soot Processes – Structure of Flame Balls at Low Lewis-number (SOFBALL)

Table 3–107. STS-83 Mission Characteristics (Continued)

Get Away Specials	None
Mission Results	The MSL-1 mission was cut short due to concerns about one of the three fuel cells. Fuel cell No. 2 had shown some erratic readings during prelaunch startup but was cleared to fly after additional checkout and test. Shortly after on-orbit operations began, the differential voltage in the No. 3 substack of fuel cell No. 2 began to rise. Shuttle flight rules required all three to be functioning properly to ensure crew safety and provide sufficient backup capability during reentry and landing. A decision was made after landing to refly the entire mission on STS-94. It was the first mission to end early since STS-44 in 1991.
Remarks	*Columbia* was outfitted with extended duration orbiter hardware for the flight.

[a] Jenkins, p. 310.

Table 3–108. STS-84 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: Charles J. Precourt PLT: Eileen M. Collins PC: Jean-Francois Clervoy (ESA) MS: Carlos I. Noriega, Edward Tsang Lu, Elena V. Kondakova (RSA), C. Michael Foale (remained on *Mir*), Jerry M. Linenger (departed *Mir* for return to Earth)
Launch	May 15, 1997, 4:07:48 a.m. EDT, Kennedy Space Center, Pad 39-A. The liftoff occurred on time following a smooth countdown.
Orbital Altitude & Inclination	160 nmi (296 km), 51.60 deg
Launch Weight (lb/kg)	249,462[a]/113,154
Landing & Postlanding Operations	May 24, 1997, 9:27:44 a.m. EDT, Runway 33, Kennedy Space Center. The orbiter landed on the second opportunity after being waved off from the first due to low clouds in the vicinity.
Rollout Distance (ft/m)	8,384/2,555
Rollout Time (seconds)	51
Mission Duration	221 hr, 19 min, 56 sec
Landed Revolution No.	143
Mission Support	STDN
Primary Objective	S/MM-06; experimentation using SPACEHAB
Deployed Satellites	None
Experiments	SPACEHAB Double Module: Double module carrying the following experiments: • Environmental Radiation Measurements • Greenhouse-Integrated Plant Experiments • Human Life Sciences Project • Protein Crystal Growth Experiments • Diffusion-Controlled Crystallization Apparatus for Microgravity (DCAM) • Gaseous Nitrogen Dewar (GND) • VDA-2 • Morphological Transition and Model Substances (MOMO)

Table 3–108. STS-84 Mission Characteristics (Continued)

Experiments	• Biorack: This multipurpose unit contained these experiments: – Cytoskeleton of the Lentil Root Statocyte – Morphology and Physiology of Loxodes After Cultivation in Space – Lymphocyte and Monocyte Intra-Cellular Signal Transduction in Microgravity – Microgravity Effects on Bone Cell Gene Expression – Microgravity and Signal Transduction Pathways in Sea Urchin Sperm – Graviperception in Starch-Deficient Plants PCG-STES: See STS-67. Liquid Motion Experiment (LME): The LME investigated inertia wave oscillations of liquids in tanks spinning around an exterior axis that was nutating under microgravity conditions. CREAM: See STS-48. EPICS: See STS-69. RME-III: See STS-28. Shuttle Ionospheric Modification with Pulsed Local Exhaust (SIMPLEX): The orbiter orbital maneuvering system thruster firings were used to create ionospheric disturbances for observation by the SIMPLEX radar sites. MSX: See STS-79.
Get Away Specials	None
Mission Results	Successful
Remarks	Linenger's 123-day stay on *Mir* and 132 days in space placed him second behind Shannon Lucid for the most time spent on-orbit by an American. Another milestone reached during his stay was the one-year anniversary of a continuous U.S. presence in space that began with Lucid's arrival at *Mir* on March 22, 1996.

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[a] Jenkins, p. 310.

Table 3–109. STS-94 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: James D. Halsell, Jr. PLT: Susan L. Still PC: Janice E. Voss MS: Michael L. Gernhardt, Donald A. Thomas PS: Roger K. Crouch, Gregory T. Linteris
Launch	July 1, 1997, 2:02:00 p.m. EDT, Kennedy Space Center, Pad 39-A. The liftoff was delayed about 12 minutes because of unacceptable weather conditions in the launch area in the event a return-to-launch site abort was necessary. The launch window originally was targeted to open at 2:37 p.m., July 1. On June 20, NASA managers decided to move the launch back 47 minutes to 1:50 p.m. to avoid forecasted afternoon thundershowers.
Orbital Altitude & Inclination	160 nmi (296 km), 28.45 deg
Launch Weight (lb/kg)	260,249[a]/118,047
Landing & Postlanding Operations	July 17, 1997, 6:46:34 a.m. EDT, Runway 33, Kennedy Space Center. The landing occurred at the first opportunity.
Rollout Distance (ft/m)	8,892/2,710
Rollout Time (seconds)	55
Mission Duration	370 hr, 44 min, 36 sec
Landed Revolution No.	250
Mission Support	STDN
Primary Objective	Reflight of the MSL-1
Deployed Satellites	None
Experiments	Reflight of STS-83 MSL-1: MSL-1 housed a collection of microgravity experiments inside a Spacelab long module. The laboratory featured material science investigations. The facilities and their experiments were: • LIF: – Measurement of Diffusion Coefficient by Shear Cell Method – Diffusion of Liquid Metals – Diffusion in Liquid Lead-Tin-Telluride – Impurity Diffusion in Ionic Metals – Liquid Phase Sintering II – Diffusion Processes in Molten Semiconductors

Table 3–109. STS-94 Mission Characteristics (Continued)

Experiments	• Expedite the Processing of Experiments to the Space Station Rack (EXPRESS): – Physics of Hard Sphere Experiment – Astro/Plant Generic Bioprocessing Apparatus (AstroPGBA) • TEMPUS: – Thermophysical Properties of Undercooled Metallic Melts – Thermophysical Properties of Advance Materials in the Undercooled Liquid State – Measurement of the Surface Tension of Liquid and Undercooled Metallic Melts by Oscillating Drop Technique – Study of the Morphological Stability of Growing Dendrites by Comparative Dendrite Velocity Measurements on Pure Ni and a Dilute Ni-C Alloy in the Earth and Space Laboratory – Undercooled Melts of Alloys with Polytetrahedral Short-Range Order – Thermal Expansion of Glass Forming Metallic Alloys in the Undercooled State – Experiments on Nucleation in Different Flow Regimes – Alloy Undercooling Experiments – Measurement of Surface Tension and Viscosity of Undercooled Liquid Metals – AC Calorimetry and Thermophysical Properties of Bulk Glass-Forming Metallic Liquids • CM-1: – Laminar Soot Processes – SOFBALL • Droplet Combustion Apparatus: – Droplet Combustion Experiment – Fiber-Supported Droplet Combustion • Middeck Glove Box: – Coarsening in Solid-Liquid Mixtures – Bubble and Drop Nonlinear Dynamics – A Study of Fundamental Operation of a Capillary-Driven Heat Transfer (CHT) Device in Microgravity – Internal Flows in a Free Drop • Protein Crystallization Apparatus: – Protein Crystallization Apparatus for Microgravity – Second Generation Vapor Diffusion Apparatus – Handheld Diffusion Test Cells • Measuring Microgravity: – SAMS – QSAMS – OARE – MMA

Table 3–109. STS-94 Mission Characteristics (Continued)

Experiments	Cryogenic Flexible Diode Experiment (CRYOFD): This experiment determined the behavior of cryogenic two-phase thermal control components in microgravity; demonstrated oxygen and methane heat pipe startups from a super-critical condition, demonstrated operations; verified analytical performance models; and established the correlation between 1g and microgravity thermal performance. A secondary objective was to validate the performance of an American Loop Heat Pipe with Ammonia (ALPHA). SAREX-II: See STS-35. MSX: See STS-79.
Get Away Specials	None
Mission Results	Successful
Remarks	*Columbia* was outfitted with extended duration orbiter hardware for the flight. The mission was the first reflight of the same vehicle, crew, and payloads. It also was the first reservicing of a primary payload, MSL-1, in the orbiter.

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[a] Jenkins, p. 310.

Table 3–110. STS-85 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Curtis L. Brown, Jr. PLT: Kent V. Rominger PC: N. Jan Davis MS: Robert L. Curbeam, Jr., Stephen K. Robinson PS: Bjarni V. Tryggvason (CSA)
Launch	August 7, 1997, 10:41:00 a.m. EDT, Kennedy Space Center, Pad 39-A. The liftoff was on time following a smooth countdown.
Orbital Altitude & Inclination	173 nmi (320 km), 51.6 deg
Launch Weight (lb/kg)	249,696[a]/113,260
Landing & Postlanding Operations	August 19, 1997, 7:07:59 a.m. EDT, Runway 33, Kennedy Space Center. A landing opportunity on August 18 was waved off due to threat of ground fog in the local area.
Rollout Distance (ft/m)	8,792/2,680
Rollout Time (seconds)	68
Mission Duration	284 hr, 27 min, 00 sec
Landed Revolution No.	189
Mission Support	STDN
Primary Objective	Deployment and retrieval of CRISTA-SPAS-2
Deployed Satellites	Deployed and retrieved CRISTA-SPAS-2
Experiments	Technology Applications and Science (TAS-1): The overall objective was to fly more science experiments using better, faster, and cheaper avionics and processes. This Hitchhiker payload carried the following experiments: • SOLCON • Infrared Spectral Imaging Radiometer (ISIR) • Shuttle Laser Altimeter (SLA) • Critical Viscosity of Xenon (CVX) • SEM • Two Phase Flow (TPF) • Cryogenic Flight Experiment (CFE) • Stand Alone Acceleration Measurement Device and the Wide Band Stand Alone Acceleration Measurement Device (SAAMD/WBSAAMD)

Table 3–110. STS-85 Mission Characteristics (Continued)

Experiments	Manipulator Flight Demonstration (MFD): Sponsored by NASDA, this experiment evaluated the use of the Small Fine Arm planned to be part of the Japanese Experiment Module's remote manipulator system on the ISS. It also included two other experiments: • Two-Phase Fluid Loop Experiment (TPFLEX) • Evaluation of Space Environment and Effects on Materials (ESEM)
	EH-2: The IEH-2 consisted of four experiments with the common objective of investigating the uncertainty and long-term variation in the absolute solar extreme ultraviolet (EUV) flux and EUV emissions of the Jupiter Io plasma torus system. The experiments were: • SEH-2 • UVSTAR • Distribution and Automation Technology Advancement–Colorado Hitchhiker and Student Experiment of Solar Radiation (DATA-CHASER) • GLO-5 and GLO-6
	BDS-3: See STS-70.
	PCG-STES: See STS-67.
	MSX: See STS-79.
	SIMPLEX: See STS-84.
	Southwest Ultraviolet Imaging System (SWUIS): This imaging system was used primarily to view the Hale-Bopp comet. The SWUIS also performed ultraviolet astronomy; planetary and cometary imaging; terrestrial airglow and atmospheric background imaging; auroral imaging; and studied Shuttle glow and vehicle plume evaluations.
	BRIC-10: See STS-64.
	SSCE: See STS-41.
Get Away Specials	G-572 Customer: Bellarmine College, University of Utah, Utah State University Hearts in Space: This experiment investigated the effect of weightlessness on physical factors contributing to cardiac function.
	G-745 Customer: Students and Teachers of Mayo High School in Rochester, Minnesota This experiment investigated root growth during a Shuttle mission.

Table 3–110. STS-85 Mission Characteristics (Continued)

Space Experiment Module	CAN-DO, Charleston, South Carolina Several active experiments flew within CAN-DO's single module, including the following: a study of a revival of a Polypodium Polypodioides plant; the measurement of radiation of the internal environment of the module; the recording of "sounds" within the module with a cassette recorder and vibration sensor; and the observation of the dispersion of paint in microgravity. Also, the module included passive and active experiments from other school districts.
Mission Results	Successful

[a] Jenkins, p. 310.

Table 3–111. STS-86 Mission Characteristics

Vehicle	OV-104 *Atlantis*
Crew	CDR: James D. Wetherbee PLT: Michael J. Bloomfield MS: Vladimir G. Titov (RSA), Scott E. Parazynski, Jean-Loup J.M. Chretien (French Air Force), Wendy B. Lawrence, David A. Wolf (remained on *Mir*), C. Michael Foale (departed *Mir* for return to Earth)
Launch	September 25, 1997, 10:34:19 p.m. EDT, Kennedy Space Center, Pad 39-A. On-time liftoff occurred after final approval for flight to *Mir* given earlier in day by NASA Administrator Goldin following his review of independent and internal safety assessments regarding safety of *Mir* and Shuttle-*Mir* docking and two independent studies that were prompted by numerous problems on the station, including a fire and a collision (see discussion of the *Mir* program later in this chapter).
Orbital Altitude & Inclination	160 nmi (296 km), 51.60 deg
Launch Weight (lb/kg)	252,035[a]/114,321
Landing & Postlanding Operations	October 6, 1997, 5:55:09 p.m. EDT, Runway 15, Kennedy Space Center. The Shuttle landed on the first opportunity after two opportunities on October 5 were waved off due to low clouds.
Rollout Distance (ft/m)	11,947/3,641
Rollout Time (seconds)	82
Mission Duration	259 hr, 20 min, 53 sec
Landed Revolution No.	169
Mission Support	STDN
Primary Objective	Seventh Shuttle-*Mir* docking; experimentation using SPACEHAB
Deployed Satellites	None
Experiments	SPACEHAB: This double module carried the following experiments: • Human Life Sciences • ISS Risk Mitigation • Interferometer To Study Protein Crystal Growth (IPCG) • Canadian Protein Crystallization Experiment (CAPE) MEEP: This *Mir* payload gathered data on human-made and natural space debris, capturing some debris for later study.

Table 3–111. STS-86 Mission Characteristics (Continued)

Experiments	SEEDS-II: This experiment passively exposed a group of tomato seeds in hand-sewn Dacron bags to the vacuum of space. Seeds flown in the payload were compared with a control group of seeds and an experimental group of seeds in an underwater habitat in Key Largo, Florida. After completion of the mission, the seeds were distributed to schools for education and outreach purposes.
	Kidsat: The Kidsat used an electronic still camera aboard the Shuttle to bring the frontiers of space exploration to a growing number of U.S. middle school classrooms via the Internet.
	CPCG: See STS-49.
	CREAM: See STS-48.
	CCM-A: See STS-80.
	SIMPLEX: See STS-84.
	ESA's European Laser Docking System: This system monitored the Shuttle's approach and departure from *Mir* using GPS receivers and optical rendezvous sensors.
Get Away Specials	None
Mission Results	Successful

[a] Jenkins, p. 310.

Table 3–112. STS-87 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Kevin R. Kregel PLT: Steven W. Lindsey MS: Kalpana Chawla, Winston E. Scott, Takao Doi (JAXA) PS: Leonid K. Kadenyuk (National Space Agency of Ukraine)
Launch	November 19, 1997, 2:46:00 p.m. EST, Kennedy Space Center, Pad 39-B. The liftoff proceeded on time. This was the first use of Pad 39-B since January following extensive modifications to the pad structure.
Orbital Altitude & Inclination	150 nmi (278 km), 28.45 deg
Launch Weight (lb/kg)	260,799[a]/118,296
Landing & Postlanding Operations	December 5, 1997, 7:20:04 a.m. EST, Runway 33, Kennedy Space Center. The Shuttle landed on the first landing opportunity.
Rollout Distance (ft/m)	8,004/2,440
Rollout Time (seconds)	57
Mission Duration	376 hr, 34 min, 2 sec
Landed Revolution No.	251
Mission Support	STDN
Primary Objective	Deployment and retrieval of SPARTAN 201-04; experimentation using the USMP-4
Deployed Satellites	Deployed and retrieved SPARTAN 201-04
Experiments	USMP-4: This payload conducted research in the areas of materials science, combustion science, and fundamental physics. USMP experiments operating without crew involvement included: • AADSF • Confined Helium Experiment (CheX) • IDGE • MEPHISTO • SAMS • OARE Experiments housed in the MGBX requiring crew involvement: • Enclosed Laminar Flames (ELF) • Wetting Characteristics of Immiscibles (WCI) • Particle Engulfment and Pushing by a Solid/Liquid Interface (PEP)

Table 3–112. STS-87 Mission Characteristics (Continued)

Experiments	Collaborative Ukrainian Experiment (CUE): The CUE was a collection of 10 plant space biology experiments that evaluated the effects of microgravity on pollination and fertilization of *Brassica rapa* (Wisconsin Fast Plants). The experiment also compared change in ultrastructure, biochemical composition, and function induced by the spaceflight environment on the photosynthetic apparatus of *Brassica rapa* seedlings at different stages of vegetative development. Teachers and Students Investigating Plants in Space (CUE-TSIPS): High school students in the United States and Ukraine performed special plant biology science experiments while viewing interactive downlinks of Payload Specialist Kadenyuk and U.S. astronauts conducting the same experiments in microgravity. Shuttle Ozone Limb Sounding Experiment/Limb Ozone Retrieval Experiment (SOLSE/LORE): A Hitchhiker payload, this experiment generated overall ozone coverage images and cross sections of the atmosphere showing ozone concentrations at different altitudes. Loop Heat Pipe/Sodium Sulfur Battery Experiment (LHP/NaSBE): A Hitchhiker payload, this experiment investigated a unique thermal energy management system using a loop heat pipe and studied the microgravity operation of sodium and sulfur liquid electrodes. Turbulent Gas-Jet Diffusion Flames (TGDF): A Hitchhiker payload, this experiment used a GAS canister to gain further knowledge of the characteristics of transitional turbulent gas-jet diffusion flames.
Get Away Specials	G-036 Customer: El Paso (Texas) Community College and Goddard Space Flight Center G-036 contained four experiments: • Cement Mixing Experiment (CME): Cement samples were mixed with water and then compared with others produced on Earth to analyze the effects of microgravity on the combination of cement and water. • Configuration Stability of Fluid Experiment (CSFE): The CSFE investigated the effects of microgravity on the configuration stability of a two-phase fluid system. • Computer (Compact) Disc Evaluation Experiment (CDEE): The CDEE investigated the effects of the exosphere, the outer fringe region of the atmosphere of a planet, on the ability of discs to retain their information. • Asphalt Evaluation Experiment (AEE): The AEE explored the effects of exposure to the exosphere on asphalt.

Table 3–112. STS-87 Mission Characteristics (Continued)

Mission Results	A malfunction of SPARTAN's attitude control system caused the rotational spin of about two degrees per second after attempts to regrapple the satellite. Planned research on SPARTAN was not performed. Other mission objectives were successfully achieved.
Remarks	To retrieve SPARTAN, Winston Scott and Takao Doi began a 7-hour, 43-minute EVA. They captured SPARTAN by hand and then completed a series of activities continuing preparations for on-orbit assembly of the ISS. Doi became the first Japanese citizen to walk in space.

[a] Jenkins, p. 310.

Table 3–113. STS-89 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Terrence W. Wilcutt PLT: Joe Frank Edwards, Jr. MS: James F. Reilly, Michael P. Anderson, Salizhan Shakirovich Sharipov (RSA), Andrew S.W. Thomas (remained on *Mir*), David A. Wolf (departed *Mir* for return to Earth) PC: Bonnie J. Dunbar
Launch	January 22, 1998, 9:48:15 p.m. EST, Kennedy Space Center, Pad 39-A. The launch originally targeted for January 15, 1998, was changed first to no earlier than January 20 and then to January 22 per request from the Russian Space Agency (RSA) to allow completion of activities on *Mir*. *Endeavour* returned to the Shuttle fleet after completing its first OMDP. *Endeavour* was the second orbiter to dock with *Mir*.
Orbital Altitude & Inclination	150 nmi (279 km), 51.60 deg
Launch Weight (lb/kg)	252,316[a]/114,449
Landing & Postlanding Operations	January 31, 1998, 5:35:09 p.m. EST, Runway 15, Kennedy Space Center. The Shuttle landed on the first opportunity.
Rollout Distance (ft/m)	9,790/2,983
Rollout Time (seconds)	70
Mission Duration	211 hr, 46 min, 55 sec
Landed Revolution No.	138
Mission Support	STDN
Primary Objective	S/MM-08; experimentation using SPACEHAB
Deployed Satellites	None
Experiments	The SPACEHAB double module carried the following experiments: • Mechanics of Granular Materials • ASTROCULTURE™ • X-Ray Detector Test • DCAM • Gaseous Nitrogen Dewar Closed Equilibrated Biological Aquatic System (CEBAS): The CEBAS mini-module was a habitat for aquatic organisms. The CEBAS conducted various gravity-related experiments in zoology, botany, and developmental biology, and interdisciplinary areas such as scientific research on artificial ecosystems.

Table 3–113. STS-89 Mission Characteristics (Continued)

Experiments	Microgravity Plant Nutrient Experiment (MPNE): This experiment tested nutrient delivery technology that would support plant growth in space. EarthKAM: Students from 51 middle schools in three nations operated a digital camera mounted in the overhead window of the Shuttle, selecting sites around the world to photograph during the Shuttle flight.
Get Away Specials	G-093 Customer: University of Michigan Vortex Ring Transit Experiment (VORTEX): The VORTEX investigated the propagation of a vortex ring through a liquid-gas interface in microgravity. G-141 Customer: German Aerospace Center and the University of Giessen, Germany Structure of Marangoni Convection in Floating Zones: Marangoni convection was studied without disturbances in microgravity. G-145 Customer: German Aerospace Center and Technical University of Clausthal, Germany Glass Fining: G-145 studied the process of glass fining or the removal of all visible gaseous bubbles from a glass melt. G-432 Customer: Chinese Academy of Sciences, Beijing, China G-432 consisted of five experiments: • Super Cooling • Processing of High Critical Test • Growth of Gallium Antimony Experiment • Liquid Phase Epitaxy • Wetability Test
Mission Results	Successful

[a] Jenkins, p. 310.

Table 3–114. STS-90 Mission Characteristics

Vehicle	OV-102 *Columbia*
Crew	CDR: Richard A. Searfoss PLT: Scott D. Altman PC: Richard M. Linnehan MS: Kathryn P. Hire, Dafydd (Dave) Rhys Williams (CSA) PS: Jay C. Buckey, James A. Pawelczyk
Launch	April 17, 1998, 2:19:00 p.m. EDT, Kennedy Space Center, Pad 39-B. The launch was postponed on April 16 for 24 hours due to difficulty with one of *Columbia*'s two network signal processors that format data and voice communications between the ground and the Space Shuttle. Network signal processor No. 2 was replaced, and the liftoff on April 17 occurred on time.
Orbital Altitude & Inclination	150 nmi (279 km), 39.00 deg
Launch Weight (lb/kg)	262,357[a]/119,003
Landing & Postlanding Operations	May 3, 1998, 12:08:59 p.m. EDT, Runway 33, Kennedy Space Center. The Shuttle landed on the first opportunity.
Rollout Distance (ft/m)	9,998/3,047
Rollout Time (seconds)	58
Mission Duration	381 hr, 49 min, 58 sec
Landed Revolution No.	255
Mission Support	STDN
Primary Objective	Conduct final Spacelab mission: Neurolab
Deployed Satellites	None
Experiments	Neurolab: The Neurolab, dedicated to study of life sciences, focused on the most complex and least understood part of the human body: the nervous system. The crew served as both experiment subjects and operators. Other subjects included rats, mice, crickets, snails, and two kinds of fish. The Neurolab teams performed the following experiments: • Autonomic Nervous System Team: – Artificial Neural Networks and Cardiovascular Regulation – Integration of Neural Cardiovascular Control in Space – Autonomic Neuroplasticity in Weightlessness – Autonomic Neurophysiology in Microgravity

Table 3–114. STS-90 Mission Characteristics (Continued)

Experiments	• Sensory Motor Performance Team: – Frames of Reference and Internal Models – Visuo-Motor Coordination During Spaceflight – Role of Visual Cues in Spatial Orientation • Vestibular Team: – Visual-Otolithic Interactions in Microgravity – Spatial Orientation of the Vestibulo-Ocular Reflex • Sleep Team: – Sleep and Respiration in Microgravity – Clinical Trial of Melatonin as Hypnotic for Neurolab Crew • Mammalian Development Team: – Neuro-Thyroid Interaction on Skeletal Isomyosin Expression in Zero Gravity – Neuronal Development Under Conditions of Spaceflight – Reduced Gravity: Effects in the Developing Nervous System – Microgravity and Development of Vestibular Circuits – Effects of Microgravity on Neuromuscular Development – Postnatal Development of Aortic Nerves in Space – Effects of Gravity on Postnatal Motor Development • Adult Neuronal Plasticity Team: – Central Nervous System Control of Rhythms and Homeostasis During Spaceflight – Anatomical Studies of Central Vestibular Adaptation – Multidisciplinary Studies of Neural Plasticity in Space – Ensemble Neural Coding of Place and Direction in Zero-G – Effects of Microgravity on Gene Expression in the Brain • Aquatic Team: – Chronic Recording of Otolith Nerves in Microgravity – Development of Vestibular Organs in Microgravity • Neurobiology Team: – Development of an Insect Gravity Sensory System in Space

Table 3–114. STS-90 Mission Characteristics (Continued)

Experiments	Shuttle Vibration Forces (SVF): Measured dynamic forces acting between the Space Shuttle and a canister attached to the Shuttle sidewall during the mission. BDS-04: The crew performed the following two cell biology experiments under controlled conditions on small samples of material: • Human Renal Cell Experiment • Microgravity Induced Differentiation of HL-60 Promyelocytic Leukemia Cell
Get Away Specials	G-197 Customer: Lockheed Martin Astronautics, Denver, National Institute of Standards and Technology (NIST), and Ames Research Center, Mountain View, California This experiment demonstrated pulse tube cooling technology in the zero gravity environment of space to gain operational experience with the smallest such cryocooler yet built. G-772 Customer: University of Colorado, Boulder Collisions into Dust Experiment (COLLIDE): The COLLIDE analyzed the gentle collisions of dust particles in space to learn more about the sources of dust in planetary rings. G-744 Customer: Sierra College, Rocklin, California This experiment took ozone measurements of Earth's upper atmosphere in the ultraviolet 200-nanometer to 400-nanometer spectral range using a charge coupled device-based spectrometer.
Mission Results	The mission was successful except for the results from the Mammalian Development Team, which had to reprioritize its science activities because of the unexpected high mortality rate of neonatal rats on board.
Remarks	*Columbia* was outfitted with extended duration orbiter hardware for the flight. Astronaut Kathryn Hires was the first Kennedy Space Center employee to be chosen as an astronaut candidate.

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[a] Jenkins, p. 310.

Table 3–115. STS-91 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Charles J. Precourt PLT: Dominic L. Pudwill-Gorie MS: Franklin R. Chang-Diaz, Wendy B. Lawrence, Janet Lynn Kavandi, Valery Victorovitch Ryumin (RSA)
Launch	June 2, 1998, 6:06:24 p.m. EDT, Kennedy Space Center, Pad 39-A. The countdown proceeded smoothly except for a slight delay in operations to load the external tank with cryogenic propellant to evaluate a few technical issues. As planned, launch managers determined the exact orbital location of the *Mir* space station during the countdown's T-9-minute built-in hold. The decision was then made to launch *Discovery* at 6:06 p.m. to achieve optimum Shuttle system performance and to accommodate Shuttle-*Mir* rendezvous activities.
Orbital Altitude & Inclination	204 nmi[a] (379 km), 51.60 deg
Launch Weight (lb/kg)	259,653[b]/117,777
Landing & Postlanding Operations	June 12, 1998, 2:00:18 p.m. EDT, Runway 15, Kennedy Space Center. The Shuttle landed on the first landing opportunity.
Rollout Distance (ft/m)	11,730/3,575
Rollout Time (seconds)	64
Mission Duration	235 hr, 54 min, 00 sec
Landed Revolution No.	154
Mission Support	STDN
Primary Objective	S/MM-09; experimentation using SPACEHAB
Deployed Satellites	None
Experiments	AMS: This experiment was a collaboration between NASA and the U.S. Department of Energy. This was the first time a high-energy particle magnetic spectrometer was placed in orbit. The spectrometer was designed to detect and catalogue, with a high degree of precision, high-energy charged particles (including antimatter) outside Earth's atmosphere. During its time aboard the Shuttle, a complete system check was performed to ensure it would function properly on the Space Station. The spectrometer also carried out a search for anti-helium and anti-carbon nuclei and measured the spectrum of antiprotons.

Table 3–115. STS-91 Mission Characteristics (Continued)

Experiments	Shuttle-*Mir* Science: • Advanced Technology–Commercially initiated research to evaluate new technologies and techniques using the *Mir* space station and the Shuttle as a testbed. – ASTROCULTURE™ – X-Ray Detector Test (XDT) – Optizon Liquid Phase Sintering Experiment (OLiPSE) • Earth Sciences–Visual observations and photography of sites of interest, • Human Life Sciences–Investigations focusing on crew members' adaptation to weightlessness in terms of skeletal muscle and bone changes, cardiovascular acclimatization, and psychological interactions. The investigations continued to characterize the integrated human response to a prolonged presence in space. – Crew member and Crew-Ground Interactions During NASA-*Mir* – Magnetic Resonance Imaging (MRI) – Autonomic Investigations (Cardio) – Bone Mineral Loss and Recovery After Shuttle/*Mir* Flights (Bone) – Assessment of Humoral Immune Function During Long-Duration Spaceflight (Immunity) – Renal Stone Risk Assessment During Long-Duration Spaceflight (Renal-2) • ISS Risk Mitigation – CREAM – Space Portable Spectroreflectometer (SPSR) – Test of Portable Computer System (TCPS) Hardware – RME • Microgravity–Materials science research – Microgravity Isolation Mount (MIM) Facility Operations PCG-Dewar – SAMS – QUELD – Biotechnology System Diagnostic Experiment (BTSDE) Reflight – Biotechnology System Coculture (COCULT) – DCAM CPCG: See STS-49. SSCE: See STS-41. Growth and Morphology, Boiling and Critical Fluctuations in Phase Separating Supercritical Fluids (GMSF): This experiment increased knowledge in the fundamental science of critical fluids. SIMPLEX: See STS-84.

Table 3–115. STS-91 Mission Characteristics (Continued)

Get Away Specials	G-648 Customer: Canadian Space Agency's Microgravity Sciences Program and University of Moncton, New Brunswick ACTORS: The ACTORS processed organic materials in space where the gravitational forces were minimal to compare thin films. G-765 Customer: Canadian Space Agency and several other partners • Microgravity Industry Related Research for Oil Recovery (MIRROR): The MIRROR conducted research to develop new technologies to extract oil from Earth and clean up accidental oil spills. G-090 Customer: Utah State University designed this GAS payload to carry the following four experiments for high school students: • Chemical Unit Process (CUP)–Shoshone-Ba Junior/Senior High School, Fort Hall Reservation, Idaho • Nucleic Boiling–Box Elder High School, Brigham City, Utah • Crystal Growth Experiment–Moscow (Idaho) High School and Moscow University, Idaho • Popcorn/Radish Experiment–St. Vincent Elementary School, Salt Lake City, Utah G-743 Customer: Broward (Davie, Florida) and Brevard (Cocoa, Florida) Community Colleges and Belen Jesuit Preparatory School (Miami, Florida) A genotoxicology experiment determined the degree to which DNA was damaged by exposure to cosmic radiation in a space environment.

Table 3–115. STS-91 Mission Characteristics (Continued)

Space Experiment Module	SEM-03: • Effect of Microgravity on Crossing-Over in Sordaria Fimicola–Shoreham, New York Wading River High School • Crystal Growth in Microgravity–Tomasita Young Astronauts Club, Albuquerque, New Mexico • Norfolk, Virginia Public Schools Science and Technology Advanced Research (NORSTAR) experiments: – Effect of microgravity on development of Daphnia, Eubranchipus, and Triops eggs – Separation of immiscible fluids in microgravity • Boy Scouts Troop 177 and Four Rivers District, Gambrills, Maryland–Merit Badge Madness • CAN-DO Project, Charleston, South Carolina, experiments: • MAVIS–Magnetic Attraction Viewed In Space • BEST–Big Experiment in Small Tubes • Cosmic Radiation Effects on Programmable Logic Devices (CREPLD)–Purdue University, West Lafayette, Indiana • Woodmore Elementary School, Mitchellville, Maryland (WESTAR) SEM-05: • Effect of Spaceflight on Food Yield–Chesapeake Bay Girl Scout Council, Salisbury, Maryland • Exposure of the Space Experiment Module to the Space Environment–Excel Interactive Science Museum, Salisbury, Maryland • Comparative Microgravity Response of Fungi and Mold–Grand Coulee, Washington Elementary School • Effect of Microgravity on Plant Seeds–Olin-Sang-Ruby Union Institute, Ocononmowoc, Wisconsin • Flower Garden in Space–Virginia Parent Teachers and Students Association, Accomac, Virginia • Effects of Microgravity on Sordaria Fimicola–Wicomico High School, Salisbury, Maryland
Mission Results	Successful
Remarks	After undocking of *Discovery* from *Mir*, the crew carried out a gas release procedure consisting of the release of a tracer gas composed of acetone and biacetyl into the depressurized Spektr module on *Mir*. The procedure was designed to enable Shuttle astronauts to document the ionization glow from the gas through any hole in Spektr's hull before sunrise and any fluorescent glow from the gas after sunrise.

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[a] Altitude not found in NASA Mission Archives. Source of altitude is Jenkins, p. 311.

[b] Jenkins, p. 311.

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Table 3–116. STS-95 Mission Characteristics

Vehicle	OV-103 *Discovery*
Crew	CDR: Curtis L. Brown, Jr. PLT: Steven W. Lindsey PC: Stephen K. Robinson MS: Scott E. Parazynski, Pedro Duque (ESA) PS: Chiaki Mukai (JAXA), Senator John H. Glenn, Jr.
Launch	October 29, 1998, 2:19:34 p.m. EST, Kennedy Space Center, Pad 39-B. The countdown proceeded to T-9 minutes but was held an additional 8.5 minutes while the launch team discussed the status of a master alarm heard during cabin leak checks after hatch closure. When the count picked up and the Orbiter Access Arm was retracted, the Range Safety Officer (RSO) requested a hold at T-5 minutes due to an aircraft in the restricted air space around Kennedy Space Center. When the aircraft cleared the area, the RSO gave the all-clear signal and the countdown proceeded. Following main engine start, but before booster ignition, the drag chute compartment door fell off but, according to the NASA Space Shuttle Mission Chronology for STS-95, "posed no problem for the mission."[a] Managers decided not to deploy the chute upon landing. This was the first flight of the Space Shuttle Main Engine–Block II.
Orbital Altitude & Inclination	310 nmi (574 km), 28.45 deg
Launch Weight (lb/kg)	263,987[b]/119,743
Landing & Postlanding Operations	November 7, 1998, 12:04:00 p.m. EST, Runway 33, Kennedy Space Center. Landed on first opportunity.
Rollout Distance (ft/m)	9,508/2,898
Rollout Time (seconds)	59
Mission Duration	213 hr, 14 min, 57 sec
Landed Revolution No.	134
Mission Support	STDN
Primary Objective	Experimentation using SPACEHAB; deployment and retrieval of SPARTAN 201; operation of HOST: return of John Glenn to flight
Deployed Satellites	Deployed and retrieved SPARTAN 201

Table 3–116. STS-95 Mission Characteristics (Continued)

Experiments	The SPACEHAB Single Module experiments included: • Vestibular Function Experiment Unit (VFEU) • BRIC • Oceaneering SPACEHAB Refrigerator Freezer (OSRF) • OCC 3-DMA • AGHF • Facility for Adsorption and Surface Tension (FAST) • APCF 3-DMA • BIOBOX • Self-Standing Drawer-Morphological Transition and Model Substances (SSD-MOMO) • Osteoporosis Experiment in Orbit (OSTEO) • NIH-C8 • Clinical Trial of Melatonin as Hypnotic for Space Crew (SLEEP-2) • Protein Turnover During Space Flight (PTO) • CPCG-PCF • CPCG-CVDA • MGBX • MGBX–Colloidal Disorder Order Transition (MGBX-CDOT) • MGBX–Colloidal Gelation Experiment Transition (MGBX-CGEL) • Commercial Instrumentation Technology Associates (ITA) Biomedical Experiments (CIBX) • CGBA 1 • ASC-8 • ADSEP • Protein Crystallization Apparatus for Microgravity-1 (PCAM-1) • Biotechnology Dynamics-A (BIODYN-A) • Aerogel • MBGX-Internal Flows in a Free Drop (MGBX-IFFD) • Microencapsulation Electrostatic Processing System (MEPS) The HOST Platform experiments: • Tested flight of NICMOS cooler, planned for installation into the Hubble Space Telescope • Verified the zero-gravity operation of the Reverse Turbo Brayton Cycle Cooler/CPL system • Tested flight of the Hubble Space Telescope 486 computer, planned for installation into the Hubble Space Telescope • Tested flight of the solid state recorder and correlated to known Hubble Space Telescope flight performance • Verified the operation of the Fiber-Optic Flight Experiment, a fiber-optic data link between the crew cabin and the payload bay

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Table 3–116. STS-95 Mission Characteristics (Continued)

Experiments	The IEH-03 experiments consisted of: • SEH • UVSTAR • STAR-LITE • CONCAP IV (see STS-57) • Petite Amateur Navy Satellite (PANSAT) • SOLCON Cryogenic Thermal Storage Unit Flight Experiment (CRYOTSU): Fifth in a series of Cryogenic Test Bed flights. These experiments consisted of: • 60 K Thermal Storage Unity (TSU) • Cryogenic Capillary Pump Loop (CCPL) • Cryogenic Thermal Switch (CTSW) • Phase Change Upper End Plate (PCUEP) E-Nose: The E-Nose was an environmental monitoring instrument that detected and identified a wide range of organic and inorganic molecules down to the parts-per-million level. PCG-STES: See STS-49. BRIC: See STS-64.
Get Away Specials	G-467 Customer: ESA This experiment investigated the performance of a two-phase CPL with two advanced evaporators, a two-phase Vapor Quality Sensor (VQS), and a control reservoir. G-779 Customer: Bellarmine College Louisville, Kentucky This experiment examined the role of gravitationally dependent hydrostatic pressure effects on the adaptation of the cardiovascular system to the microgravity environment of spaceflight. GAS canisters that were carried on the IEH-03 Hitchhiker: G-764 Customer: University of Bremen, Germany and Zentrum fur Angewandte Raumfahrttechnologie und Mikrogravitation (ZARM) Cosmic Dust Aggregation (CODAG): The CODAG experiment simulated the aggregation of dust particles and dynamics of dust clouds that occurred in the early stages of the formation of our solar system. G-238 Customer: American Institute of Aeronautics and Astronautics and DuVal High School, Lanham, Maryland Roach Experiment: This experiment studied the effects of space on the life cycle of the American cockroach.

Table 3–116. STS-95 Mission Characteristics (Continued)

Space Experiment Module	SEM-04: This canister contained the following eight student experiment modules, part of an educational initiative to increase student access to space. • The Effect of Microgravity and Temperature on Human Tissue and Human Used and Consumed Items–Blue Mountain School, Floyd, Virginia. • Effects of Microgravity on an Object's Physical Characteristics–Dowell Elementary School, Marietta, Georgia • The Effect of Cosmic Radiation on Wisconsin Fast Plants and the Development of Brine Shrimp Eggs and Chia Seeds–Fort Couch Middle School, Upper Saint Clair, Pennsylvania Monrovia Elementary School, Madison, Alabama • The Effects of Microgravity on Surface Tension–Glenbrook North High School, Northbrook, Illinois • Growing "Montello" Transglobally–Montello High School, Montello, Wisconsin; Istituto Technico Commerciale Riccatl, Treviso, Italy • Analysis of Three-Dimensional Sprag Performance in a Microgravity Environment–University of Maryland, College Park, Maryland • The Effect of Microgravity and Temperature on Mold Growth–West Richland Elementary School, Noble, Illinois • Woodmore Elementary School, Teaching And Researching–2 (WESTAR-2)/ GERMINAcion ARgentina (GERMINAR)–The Effect of Microgravity on Seed Growth and Survival Woodmore Elementary School, Mitchellville, Maryland; Colegio Santa Hilda, Buenos Aires, Argentina
Mission Results	Successful
Remarks	This was the first time a U.S. President (President William J. Clinton) attended a Shuttle launch.[c]

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[a] "Space Shuttle Mission Chronology: STS-95," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-95.htm* (accessed November 30, 2005).

[b] Jenkins, p. 311.

[c] "The First U.S. Launch for the International Space Station: Wrapping Up a Successful Year of Space Shuttle Missions," *Spaceport News* 37, no. 25 (December 18, 1998): 1, 4.

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Table 3–117. STS-88 Mission Characteristics

Vehicle	OV-105 *Endeavour*
Crew	CDR: Robert D. Cabana PLT: Frederick R. Sturckow MS: Jerry L. Ross, Nancy J. Currie, James H. Newman, Sergei K. Krikalev (RSA)
Launch	December 4, 1998, 3:35:34 a.m. EST, Kennedy Space Center, Pad 39-A. The originally scheduled launch of *Endeavour* on December 3 was postponed for 24 hours when time ran out on the launch window. About T-4 minutes in the launch countdown, after orbiter hydraulic systems were powered on, a master alarm associated with hydraulic system No. 1 in the crew cabin was noted. The countdown was held at T-31 seconds to further assess the situation. Shuttle system engineers attempted to quickly complete an assessment of the suspect hydraulic system and eventually gave an initial "go" to resume the countdown. With only seconds to respond, launch controllers were unable to resume the countdown in time to launch within the remaining window. The launch was completed on time on December 4.
Orbital Altitude & Inclination	173 nmi (320 km), 51.60/31.363 deg
Launch Weight (lb/kg)	239,059[a]/108,435
Landing & Postlanding Operations	December 15, 1998, 10:53:29 p.m. EST, Runway 15, Kennedy Space Center. Landing made on the first opportunity.
Rollout Distance (ft/m)	8,343/2,543
Rollout Time (seconds)	44
Mission Duration	283 hr, 17 min, 3 sec
Landed Revolution No.	185
Mission Support	STDN
Primary Objective	To deliver the first U.S. ISS module Unity and assemble with the first Russian ISS module Zarya, already in space
Deployed Satellites	Argentinean National Commission of Space Activities' Satelite de Aplicaciones/Cientifico-A (SAC-A)

Table 3–117. STS-88 Mission Characteristics (Continued)

Experiments	MightySat 1: The MightySat 1 was a non-recoverable all-composite spacecraft structure and experiments integrated with a Hitchhiker Ejection System. The program was dedicated to providing frequent, inexpensive, on-orbit demonstrations of space system technologies. The experiments were: • Advanced Composite Structure • Advanced Solar Cell • Microsystem and Packaging for Low Power Electronics
	Assessment of Human Factors Configuration A: The experiment analyzed human-machine, human-environment, and human-human interfaces.
	Effects of Microgravity on Cell-Mediated Immunity and Reactivation of Latent Viral Infections: This experiment assessed the immune system function using the immune cells from the standard Flight Medicine blood draw. The objective was to examine the mechanisms of spaceflight-induced alterations in the human immune function and latent virus shedding.
	Individual Susceptibility to Post-Spaceflight Orthostatic Intolerance: This experiment investigated mechanisms responsible for differences in post-spaceflight orthostatic intolerance to customize countermeasure protocols.
	Interaction of the Space Shuttle Launch and Entry Suit and Sustained Weightlessness on Egress: This experiment identified the impact of the Launch Entry Suit/Advanced Crew Escape Suit (LES/ACES) and sustained weightlessness on egress locomotion mechanical efficiency as measured by oxygen consumption and gait change.
	Low Iodine Residual System: This system used a newly developed technology that replaced the Galley Iodine Removal Assembly (GIRA) to reduce the concentration of iodine in the Shuttle potable water system, demonstrating that iodine concentrations in Shuttle drinking water can be reduced to medically acceptable levels while maintaining microbial control in the water distribution system.
	Single String Global Positioning System: This system demonstrated GPS performance and operation during orbiter ascent, on-orbit operations, entry, and landing phases using a modified military GPS receiver processor and existing orbiter GPS antennas.

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Table 3–117. STS-88 Mission Characteristics (Continued)

Experiments	Space Integrated Global Positioning System/Inertial Navigation System (SIGI): The SIGI mitigated the technical and schedule risks of applying this new technology to the Shuttle navigation systems by evaluating the systems' performance in spaceflight. Structural Dynamics Model Validation: This test excited the structural dynamics of the joined Shuttle and ISS to acquire several critical natural frequencies and their corresponding structural damping to allow confirmation of the acceptability of the Shuttle primary jet control algorithm tuning before attitude control using the algorithm. USA SAFER Flight Demonstration: This demonstration showed, through an end-to-end on-orbit functional checkout, that the USA SAFER design performed as expected. ICBC: The ICBC was a 65-mm color motion picture camera system used to film the Unity installation onto the orbiter docking system; the Zarya rendezvous; docking; EVA tasks; separation burn; and flyaround.
Get Away Specials	G-093R Customer: University of Michigan (Ann Arbor) Students for the Exploration and Development of Space Vortex Ring Transit Experiment: Investigated the propagation of a vortex ring through a liquid-gas interface in microgravity.
Space Experiment Module	SEM-07: This module contained 11 experiments as part of an educational initiative to increase student access to space.
Mission Results	Successful

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[a] Jenkins, p. 311.

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Table 3–118. Space Station Freedom *Prime Contractor*[a]

Prime Contractor/ NASA Center	Work Package Description	Phase I Value	Phase II Value	Partner Companies
Boeing Aerospace/ Marshall Space Flight Center	Work Package 1: Laboratory and habitation modules; resource node structures; airlock systems; environmental control/life support; thermal/video/ audio systems; logistics elements	$1.6 billion	$25 million	Teledyne Brown; Lockheed; Hamilton Standard; Garrett AiResearch; Grumman; ILC; Fairchild-Weston
McDonnell Douglas Astronautics/Johnson Space Center	Work Package 2: Truss structure; mobile servicing transporter; airlocks; resource node outfitting; data management; communications and tracking; guidance; navigation and control; EVA systems; propulsion; thermal control	$2.6 billion	$140 million (Dual-keel structure)	IBM; Lockheed; GE/RCA; Honeywell; Spar Astro
General Electric Astro-Space/ Goddard Space Flight Center	Work Package 3: Polar platform; two attach points on crewed base; integrated telerobotic servicer; defined satellite servicing facility	$895 million	$570 million (Co-orbit platform; three more attach points; satellite servicing facility)	TRW
Rockwell International Rocketdyne Division/ Lewis Research Center	Photovoltaic power generation system	$1.6 billion	$740 million (Solar dynamic power system)	Ford Aerospace; Harris; Garrett; General Dynamics; Lockheed

[a] "Space Station *Freedom* Contract Negotiations Concluded," *NASA News* Release 88-132, September 28, 1988. Also "Space Station Prime Contracts Awarded at Last," *Interavia* (September 1988): 18.

Table 3–119. Space Station Freedom *Characteristics (May 1992*[a]*)*

Element	Shape	Characteristic
Station end-to-end length		108 m (353 ft)
Station total weight		281,430 kg (309.6 tons)
Truss assembly and equipment size	Hexagonal	Length: 65.9 m (216.0 ft) Width: 3.7 m by 4.9 m (12 ft by 16 ft)
Truss assembly and equipment weight		146,000 kg (160.6 tons)
U.S. laboratory size	Cylindrical	8.4 m by 4.4 m (27.4 ft by 14.5 ft)
U.S. laboratory weight		15,545 kg (17.1 tons)
U.S. habitation module size	Cylindrical	8.4 m by 4.4 m (27.4 ft by 14.5 ft)
U.S. habitation module weight		16,182 kg (17.8 tons)
Japanese laboratory	Cylindrical	10.6 m by 4.0 m (34.8 ft by 13.1 ft)
Japanese Exposed Facility	Cylindrical	5.0 m by 5.6 m (16.4 ft by 18.4 ft)
Japanese module weight		32,818 kg (36.1 tons) (both laboratory and exposed facility)
International standard payload racks		1 m (3.5 ft) wide
U.S. resource nodes size	Cylindrical	Three each 5.2 m by 4.4 m (17 ft by 14.5 ft); centrifuge in third resource node
U.S. resource node weight		Two nodes and cupola: 23,545 kg (25.9 tons)
Canadian Mobile Servicing System		
Space System Remote Manipulator		55 ft (16.8 m)
Space System Remote Manipulator capacity		113,398 kg (250,000 lb)
Special Purpose Dexterous Manipulator		12 ft (3.6 m) (two 6-ft (1.8-m) arms)
ESA Columbus Free-Flying laboratory	Cylindrical	11.8 m (38.7 ft) by 4.5 m (14.7 ft)
Solar arrays size	Rectangular	12 m (39 ft) and 34 m (112 ft)
Solar arrays weight		7,909 kg (8.7 tons) (does not include truss)
Number of cells per array wing		32,800
Number of solar cells for six array wings		196,800

Table 3–119. Space Station Freedom *Characteristics (May 1992[a]) (Continued)*

Element	**Shape**	**Characteristic**
Power generation		120 volts DC, 18.75 kW at man-tended capability with at least 11 kW available to researchers. Would grow to 56.25 kW in the follow-on phase (permanently tended capability), with nominal 30 kW available for users, 26.25 kW available for housekeeping[b]
Crew		Four persons (two dedicated for payload operations and two researchers), growing to eight crew in the follow-on phase
Altitude		335 km–460 km (208 nmi–285 nmi)
Inclination		28.5 degrees

[a] "Space Station *Freedom*, Gateway to the Future," National Aeronautics and Space Administration, May 1992 (NASA History Office Folder 009554). Also *Space Station Freedom Media Handbook,* 1992, p. 25.

[b] *Space Station Freedom User's Guide,* August 1992, p. 3-3 (NASA History Office Folder 009554). Also Launius, p. 234. Power was reduced to 56.25 kW from 75 kW for permanently tended capability in a 1992 redesign.

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Table 3–120. Shuttle-Mir Flights

Mission	Dates	Orbiter	Type of Mission	Astronaut to/from *Mir*
STS-63	February 3 – February 11, 1995	*Discovery*	Rendezvous	
STS-71	June 27 – July 6, 1995	*Atlantis*	Docked	Returned Norman Thagard to Earth after 115 days in space. (Thagard was delivered to *Mir* on the Soyuz-TM 21 mission)
STS-74	November 12 – November 20, 1995	*Atlantis*	Docked	No astronaut. Delivered the docking module.
STS-76	March 22 – March 30, 1996	*Atlantis*	Docked	Delivered Shannon Lucid.
STS-79	September 19 – September 26, 1996	*Atlantis*	Docked	Returned Lucid to Earth after 188 days. Delivered John Blaha.
STS-81	January 12 – January 22, 1997	*Atlantis*	Docked	Returned Blaha to Earth after 128 days. Delivered Jerry Linenger.
STS-84	May 15 – May 24, 1997	*Atlantis*	Docked	Returned Linenger to Earth after 132 days. Delivered Michael Foale.
STS-86	September 25 – October 6, 1997	*Atlantis*	Docked	Returned Foale to Earth after 145 days. Delivered David Wolf.
STS-89	January 22 – January 31, 1998	*Endeavour*	Docked	Returned Wolf to Earth after 128 days. Delivered Andrew Thomas.
STS-91	June 2 – June 12, 1998	*Discovery*	Docked	Returned Thomas to Earth after 143 days.

Table 3–121. ISS Contributor[a]

Country/Space Agency	Component
Canada	Mobile servicing system
European Space Agency	Columbus laboratory module
Japan	Experiment module with centrifuge facility Exposed facility
Russia	Power platform Service module Functional cargo block (FGB)[b] Two research modules
United States	Integrated truss Habitation module Laboratory module Docking modules and passageway (Node 1) Joint airlock
Italy	Nodes 2 and 3 built for NASA

[a] "International Space Station Builds on 'Freedom,'" *HQ Bulletin* (April 4, 1994): 1 (NASA History Office Folder 009577); *Press Information Book,* The Boeing Company (NASA History Office Folder 16482).

[b] The first Russian module is referred to in NASA and Russian documents and Web sites as both the Functional Energy Block and the Functional Cargo Block. For uniformity, it is called Functional Cargo Block in this document. The acronym FGB comes from the Russian translation written in the Cyrillic alphabet.

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Table 3–122. ISS Major Milestones (as of April 1994[a])

Date	Event
November 1997	Russian FGB vehicle launch
December 1997	First U.S. launch
January 1998	Russian service module added, followed by the addition of the universal docking module and science power platform
May 1998	U.S. laboratory module attached (marks the beginning of human-tended science operations)
June 1998	Canadian-built robotic arm added
August 1998	Addition of the Soyuz transfer vehicle
Early 2000	ESA laboratory module added
June 2002	Assembly complete

[a] "International Space Station Builds on 'Freedom,'" *HQ Bulletin* (April 4, 1994): 1 (NASA History Office Folder 009577).

Table 3–123. ISS Assembly Schedule (June 1994[a])

Schedule	Date	Payload
First Russian element launch	November 1997	FGB
First U.S. element launch	December 1997	Node 1 (with four racks)
Human-tended capability	June 1998	U.S. lab outfitting
Three-person on-orbit capability	August 1998	Soyuz crew transfer vehicle
Japanese lab launch	March 2000	Japanese Experiment Module pressurized lab
European Space Agency lab launch	March 2001	Attached pressurized module
Habitation module launch	February 2002	U.S. habitation module
Permanent human capability	June 2002	Soyuz crew transfer vehicle

[a] *International Space Station Fact Book*, National Aeronautics and Space Administration, June 1994.

Table 3–124. Columbus Characteristics [a]

Item	Description
Total module length	687 cm (22.5 ft)
Largest diameter	448 cm (14.7 ft)
Total internal volume	75 cu meters (2,649 cu ft)
Total volume of payload racks	25 cu meters (883 cu ft)
Mass without payload	10,300 kg (22,708 lb)
Launch mass	12,800 kg, including 2,500-kg payload (28,219 lb, including 5,512-lb payload)
Maximum payload mass	8,000 kg (17,637 lb)
Maximum on-orbit mass	19,300 kg (42,549 lb)
Communications	Downlink via Artemis; downlink and uplink via TDRS
Crew size	Three
Cabin temperature	Between 16°C and 30°C (61°F and 86°F)
Air pressure	Between 959 and 1013 hPa
Total electrical power	20 kW provided by the Station
Payload power	13.5 kW
Main contractor	Daimler Benz Aerospace leading a consortium of subcontractors[b]

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[a] "Columbus: European Laboratory," ESA, *http://www.esa.int/esaHS/ESAFRG0VMOC_iss_0.html* (accessed June 14, 2005).

[b] Daimler Benz Aerospace merged with Matra Marconi Space in May 2000 to form Astrium GmbH.

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Table 3–125. Partial Revised Manifest, Revision C, Through 1999 (as of May 15, 1997[a]*)*

Date	Flight	Element
June 1998	1A/R	Functional Cargo Block
July 1998	2A	STS-88/U.S. Node 1 and two pressurized mating adapters (PMA)
December 1998	1R	Service module
December 1998	2A.1	Either service module logistics or the Interim Control Module
January 1999	3A	Integrated truss structure Z1, PMA-3, Ku-band communications system, control moment gyros
January 1999	2R	Three-person crew begins permanent presence on ISS: Soyuz provides assured crew return capability
March 1999	4A	Integrated truss structure Port 6, photovoltaic module, S-band antenna system
May 1999	5A	Lab provides initial U.S. user capability
June 1999	6A	Adds U.S. multipurpose logistics module, ultra-high frequency antenna, ISS remote manipulating system; carries second ISS crew
August 1999	7A	Joint airlock provides U.S. and Russian EVA capability, high pressure gas assembly
Phase II Complete		
October 1999	7A.1	Multipurpose logistics module, additional battery sets
December 1999	4R	Docking compartment 1 provides egress, ingress for Russia-based EVA and a Soyuz docking port

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[a] "Assembly Sequence, 5/15/97 Rev C," National Aeronautics and Space Administration, International Space Station (NASA History Office Folder 11613). Also "Station Buildup Sequence Combines Complex Hardware," *Aviation Week & Space Technology* (December 8, 1997): pp. 52–53 (History Office Folder 16949).

Table 3–126. ISS Assembly Sequence Revision D, Through 1999 (as of May 31, 1998)

Date	Flight	Launch Vehicle	Activity
November 1998	1A/R	Proton	Control Module (Functional Cargo Block)
December 1998	2A	Space Shuttle (STS-88)	Unity node, two PMAs
April 1999	1R	Proton	Service module
May 1999	2A.1	Space Shuttle (STS-96)	SPACEHAB Double Cargo Module
June 1999	3A	Space Shuttle (STS-92)	Integrated Truss Structure Z, PMA-3, Control Moment Gyros
July 1999	2R	Soyuz	Soyuz. Station begins permanent human presence
August 1999	4A	Space Shuttle (STS-97)	Integrated Truss Structure P6, photovoltaic module, radiators
October 1999	5A	Space Shuttle (STS-98)	U.S. Laboratory Module
December 1999	6A	Space Shuttle (STS-99)	Multipurpose Logistics Module, ultra-high frequency antenna, SSRMS

Table 3–127. Functional Cargo Block (Zarya) Specifications[a]

Item	Specification
Length (end-to-end)	12.6 m (41.2 ft)
Diameter at widest point	4.10 m (13.5 ft)
Solar arrays	10.7 m (35 ft) by 3.4 m (11 ft)
Gross launching mass	23,500 kg (53,020 lb)
Orbital mass	19,323 kg (42,600 lb)
Orbital operation lifetime	No less than 15 years
Orbital inclination	51.6 degrees to the equator
Preliminary orbit	220.4 km (137 mi) by 339.6 km (211 mi)
Docking orbit altitude	386.2 km (240 mi)[b]
Propellant	16 tanks together holding more than 5.4 metric tons (6 tons)
Power supply	Two solar arrays and six nickel-cadmium batteries
Power to be supplied to the U.S. segment	Can supply an average of 3 kW Daily average before docking with service module: 0.8 kW Daily average after docking with service module: 1.2 kW

[a] "Functional Energy Block," Khrunichev State Research and Production Space Center (History Office Folder 17083). Also "Zarya," ISS Element, *http://www.shuttlepresskit.com/ISS_OVR/element1.htm* (accessed June 13, 2005); "Space Station Assembly: Elements: Zarya Control Module," National Aeronautics and Space Administration, *http://spaceflight.nasa.gov/station/assembly/elements/fgb/index.html* (accessed June 17, 2005).

[b] The docking orbit altitude is the altitude at which *Endeavour* made rendezvous and captured the spacecraft to attach it to the U.S.-built Unity module. "Space Station Assembly: Elements: Zarya Control Module," *http://spaceflight.nasa.gov/station/assembly/elements/fgb/index.html* (accessed December 2, 2005).

Table 3–128. Unity Characteristics[a]

Item	Characteristic
Module length	18 ft (5.5 m)
Module diameter	15 ft (4.6 m)
Shape	Six-sided
Pressurized mating adapters length	8 ft (2.4 m)
Launch weight	25,600 lb (11,612 kg)
Ports	Six 50-in (127-cm) ports (4 radial and 2 axial)
Material	Aluminum
Lines	216 lines to carry fluids and gases
Cables	121 internal/external electrical cables using 6 mi (9.7 km) of wire
Stowage space	Four 27-cu-ft (9.8-cu-m) racks

[a] *Press Information Book, Mission Modules, Station Overview,* NASA, Boeing, pp. 5–6, 12.

Table 3–129. Zarya-Unity Orbital Events Summary[a]

Day	Date	Event
1	November 20, 1998	Proton launch, ascent, and orbit insertion of Zarya. Begin multi-axis spin for thermal control and to reduce fuel consumption.
2	November 21, 1998	Engine test burn (10 seconds duration, single engine). Television camera test. Perform perigee raising burn (single engine). Resulting orbit is 153 statute mi (246 km) by 215 statute mi (346 km).
4	November 23, 1998	Perform two burns to raise orbit; resulting orbit: 190 mi (306 km) by 238 mi (383 km).
5	November 24, 1998	Russian flight controllers place the module in its final orbit to achieve *Endeavour* rendezvous. Resulting orbit is 240 miles (386.2 km) circular.[b]
6	November 25, 1998	Perform on-board computer system test. Maneuver to test *Endeavour* capture, docking orientation. Maneuver to assess solar array performance.
8	November 27, 1998	Maneuver to test *Endeavour* capture, docking orientation. Assess solar array, battery charging performance. Begin multi-axis spin.
14	December 3, 1998	*Endeavour* launches on STS-88. Astronauts activate Shuttle Orbiter Docking System.
15	December 4, 1998	Perform Shuttle remote manipulator system, Orbiter Space Vision System, spacesuit checkout.
16	December 5, 1998	Attach Unity PMAs to the Orbiter Docking System using the Shuttle remote manipulator system.
17	December 6, 1998	Rendezvous with and capture Zarya with *Endeavour* remote manipulator system. Zarya berths to Unity PMA-1.
18	December 7, 1998	First spacewalk to connect utilities between PMA-2. Unity PMA-1, and Zarya. Activate Unity computerized control units and PMA shell heaters.
19	December 8, 1998	Pressurize PMA-1 via Zarya.
20	December 9, 1998	Second spacewalk to install early communications system antennas and cable, install computerized control sunshade, EVA aids, and remove common berthing mechanism hatch launch restraint pins.
21	December 10, 1998	ISS entered for the first time. Install and activate communications system; remove shear panels; transfer spare equipment to ISS.
22	December 11, 1998	ISS entered; complete remaining tasks; doors closed to ISS at end of day.
23	December 12, 1998	Third spacewalk to install EVA node stowage bag, perform photo documentation survey, and other tasks. ISS first element completed.

Table 3–129. Zarya-Unity Orbital Events Summary[a] (Continued)

Day	Date	Event
24	December 13, 1998	*Endeavour*/ISS undock, flyaround.
25	December 14, 1998	Perform *Endeavour* secondary payload operations.
25–34	December 14–23, 1998	Systems checkout by ground controllers through S-band communications system installed on Unity.
26	December 15, 1998	*Endeavour* returns home.

[a] "Summary Flight Plan, The International Space Station," *http://www.shuttlepresskit.com/ISS_OVR/assembly1_summary_timeline.htm* (NASA, Boeing, and United Space Alliance Web site) (accessed June 13, 2005). Also *Press Information Book, Mission Modules, Station Overview*, NASA, Boeing, p. 4.

[b] "Space Station Assembly: Elements: Zarya Control Module," *http://spaceflight.nasa.gov/station/assembly/elements/fgb/index.html* (accessed June 17, 2005).

Table 3–130. Science Laboratories Accommodations[a]

Type of Accommodation	Feature
Overall	• 30 kW average power available for payloads • 75 Mb/sec data downlink • Teleoperations • Multipayload modular environment • Standardized service interfaces for payloads
Internal payload	• 37 rack locations • Vibration-free environments • Microgravity environment: 10 locations at 1g level • 3 kW, 6 kW, and 12 kW power options • Vacuum, nitrogen, argon, helium, and carbon dioxide service options • Ethernet, video, high-rate data download • Payload volumes: more than 40 cu ft (1.1 cu m) per rack • Many racks support multiple modular sub-rack payloads • One location with an Earth-facing science-quality window
External payload	• 14 payload sites • 10 locations with active thermal control • 3 kW and 6 kW power options • Video, high-rate data downlink • Earth and stellar viewing sites • Robotic payload manipulation

[a] *Press Information Book*, p. 53.

Table 3–131. Space Station Chronology

Date	Event
January 25, 1984	President Ronald Reagan delivers State of the Union address calling for a "permanently manned space station" to be built within a decade.
February 20, 1986	*Mir* space station core sent into space on a Proton booster rocket.
March 1986	First Russian crew arrives on *Mir.*
1987	Space Station development split into two phases: the revised baseline configuration and the enhanced configuration.
1987	NASA Administrator Fletcher requests $3 million to study crew emergency return vehicles.
July 1988	President Ronald Reagan names the Space Station "Freedom."
September 28, 1988	Negotiations concluded for four 10-year contracts with Boeing Aerospace, McDonnell Douglas Astronautics, GE Astro-Space Division, and Rocketdyne Division of Rockwell International to correspond with four work packages.
June 1989	Assembly sequence is revised to allow only the Shuttle for lifting and assembling components.
July 1989	NASA forms Configuration Budget Review team headed by W. Ray Hook to develop preliminary options for ways for the program to exist within severe budget constraints threatened by Congress.
October 1989	Congress funds program at $1.8 billion, $250 million less than the administration's request.
October 1989	NASA releases a request for proposal for the Assured Crew Return Vehicle.
Late 1989	"Rephasing" of program announced to reduce risk and meet anticipated budget cut of nearly $300 million for FY 1990. First element launch remains at March 1995.
January 1990	NASA forms the External Maintenance Task Team to address EVAs needed for Station maintenance.
June 1990	NASA forms the External Maintenance Solutions Team to address problems raised by the External Maintenance Task Team and to recommend ways to reduce the number of spacewalks.
Fall 1990	White House forms the Advisory Committee on the Future of the U.S. Space Program, chaired by Norman Augustine, to assess alternative approaches and make recommendations for future civil space goals. Committee recommends reducing the Station's size and complexity.
March 1991	NASA delivers restructuring report to Congress for a smaller and simpler Station with a $30 billion price tag. Work Package 2 with GE is eliminated. A rephased assembly sequence moved first element launch to early 1996, human-tended capability to mid-1997, and permanent occupation to 2000.

Table 3–131. *Space Station Chronology (Continued)*

Date	Event
March 21, 1991	Vice President Dan Quayle and the National Space Council endorse report and redesign.
July 1991	Vice President Dan Quayle meets with Oleg Shishkin, minister of General Machine Building in the Soviet Union, to discuss a cooperative effort using the *Mir* space station for human missions.
July 31, 1991	President George H. W. Bush and Soviet President Mikhail Gorbachev sign an agreement for an astronaut to visit *Mir* and a cosmonaut to fly on the Space Shuttle.
September 27, 1991	The House Appropriations Committee recommends cutting off all funds to the Station, but the Senate agrees to a House funding bill and grants NASA its full FY 1992 funding request of $2,028,900,000 for the Space Station.
December 9, 1991	President George H. W. Bush signs NASA's funding bill.
April 1, 1992	Daniel Goldin replaces Richard Truly as NASA Administrator.
April 1992	Russian President Boris Yeltsin creates the civilian Russian Space Agency, headed by Yuri Koptev. Goldin and Koptev meet informally in Washington, DC to discuss possibilities for cooperation.
June 17, 1992	President George H. W. Bush and Russian President Yeltsin hold a summit in which the two agree to consider a joint space mission. They sign the "Agreement Between the United States of America and the Russian Federation Concerning Cooperation in the Exploration and Use of Outer Space for Peaceful Purposes" that includes a Shuttle-*Mir* mission.
June 19, 1992	Russia and the United States formally sign a new U.S.-Russian Space Cooperation Agreement and ratify a $1 million contract between NASA and Russian aerospace firm, NPO-Energia.
October 5, 1992	NASA and the Russian Space Agency sign an "Implementing Agreement Between the National Aeronautics and Space Administration of the United States of America and the Russian Space Agency of the Russian Federation on Human Space Flight Cooperation" that details cooperation called for in the June 1992 agreement.
March 9, 1993	President William J. Clinton orders NASA to undertake a redesign of the Station to reduce costs and complexity. The administration goal was $9 billion.
March 10, 1993	First meeting of the Station Redesign Team, led by Dr. Joseph Shea.
April 1993	An Advisory Committee, also known as the Vest Panel, is formed to assess redesign options.
April 3–4, 1993	President William J. Clinton and Vice President Albert A. Gore meet with Russian leaders at a summit in Vancouver, Canada, on further cooperation in space. President William J. Clinton invites Russia to participate in the new Station, and Russian President Yeltsin agrees.

Table 3–131. Space Station Chronology (Continued)

Date	Event
June 10, 1993	Advisory Committee presents final report to President William J. Clinton.
June 17, 1993	President William J. Clinton announces his selection of a reduced cost, scaled-down version of the original Space Station *Freedom*, called Alpha, with a $10.5 billion cost spanning five years. The President also directs NASA to develop an implementation plan by September 1993.
August 17, 1993	Goldin names Johnson Space Center as the host Center for the new Space Station program and Boeing as the single prime contractor.
September 1–2, 1993	United States-Russian Commission on technological cooperation in the areas of energy and space, headed by Vice President Albert A. Gore and Russian Prime Minister Viktor Chernomyrdin, meets and agrees on a three-phase structure to complete the Space Station.
September 7, 1993	President William J. Clinton formally chooses the small, four-person Alpha Station, a merger of Space Station *Freedom* and the Russian *Mir*. Congress and the administration agree to a total cost cap of $17.4 billion and a fixed annual budget of $2.1 billion. NASA slips the date for permanent habitability to September 2003.
October 16, 1993	The United States meets with international partners in Paris, France to formally inform them of the intent to invite Russia to join the Space Station program.
November 1, 1993	Goldin and Koptev sign an “Addendum to Program Implementation Plan” for Space Station Alpha describing the overall concept of the relationship between NASA and the Russian Space Agency.
November 7, 1993	Space Station partners jointly meet with the Russian Space Agency to review details of the November 1 addendum.
November 15, 1993	NASA signs a letter contract with Boeing making the company the Space Station prime contractor.
November 29, 1993	An agreement is reached for Russia to be “the primary partner” in the Space Station program, which would be designated the International Space Station. Russia agrees to cancel the planned sale of missile technology to India and would receive $100 million annually from NASA as compensation.
December 6, 1993	Space Station partners decide to formally invite Russia to join the partnership.

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Table 3–131. Space Station Chronology (Continued)

Date	Event
December 16–17, 1993	The Gore-Chernomyrdin Commission meets in Moscow. Russia to announce the Commission's acceptance of the invitation to join the Space Station program. Goldin and Koptev sign a protocol expanding the terms of the 1992 HSF Cooperation agreement and agree on Shuttle-*Mir* flights during 1995–1997. Albert A. Gore and Chernomyrdin sign a "Joint Statement on Space Station Cooperation" describing the steps needed to formally bring Russia into the Station partnership. The two parties note that NASA and the Russian Space Agency have agreed to a $400 million contract through 1997 for the Shuttle-*Mir* program and other Station development.
February 1, 1994	Space Station *Freedom* is formally terminated when contracts ending the work package contracts are ended and responsibility is consolidated in a contract with Boeing.
February 3, 1994	Phase I of the ISS begins when Cosmonaut Sergei Krikalev becomes the first Russian to fly on a U.S. spacecraft on the STS-63 Shuttle mission, inaugurating the Shuttle-*Mir* program.
March 1994	The ISS assembly schedule is revised with the first Shuttle launch moved from July 1997 to December 1997, and the completion date slipped from October 2001 to June 2002.
March 1994	The successful System Design Review marks a major technical milestone; it confirms the validity of the baseline configuration, schedule, and cost. Planned assembly is scheduled to begin in November 1997 with the Russian FGB. Assembly planned to be complete in 2002.
April 1994	Heads of the Space Station agencies meet in Washington, DC, to endorse the successful review and reaffirm Russia's part in the program.
June 23, 1994	The U.S.-Russian Joint Commission on Economic and Technological Cooperation signs a new "Joint Statement on Space Station Cooperation" reiterating the two governments' commitment to develop an integrated Space Station and to expedite Russia's involvement as a full partner in the program.
June 29, 1994	A bipartisan House coalition defeats a motion to cancel the Station.
July 1994	The Space Station Control Board approves a revised assembly sequence moving launch of Russia's service module from January to May 1998. The Board also agrees to purchase the FGB from Khrunichev to assure its availability when Station assembly begins.
August 3, 1994	The Senate rejects motion to cancel the Station.
August 31, 1994	NASA and Boeing agree on the key elements of the ISS prime contract.
September 1994	Space Station managers release another updated assembly plan incorporating a centrifuge to augment the Station's science capabilities and provide more power.

Table 3–131. Space Station Chronology (Continued)

Date	Event
1995	X-38 project begins at Johnson Space Center.
January 13, 1995	NASA and Boeing sign a $5.63 billion contract to manage the building of the core Station, including two nodes, an airlock, and laboratory and habitation modules and their integration. The contract also calls for the design and development of the Station.
February 5, 1995	NASA and the Russian Space Agency sign a protocol reflecting the contract negotiated between Boeing subcontractor Lockheed Missiles & Space and Khrunichev for the FGB.
May 1995	ISS completes tests to evaluate the Water Recovery System.
May 20, 1995	Spektr module is launched toward *Mir.*
July 1995	The orbiter *Atlantis* permanently attaches a new docking module to the *Mir* Kristall androgynous docking unit.
July 1995	The House defeats an attempt to cut off Station funding.
September 1995	The Senate defeats a motion to cut off Station funding.
Mid-September 1995	By this date, the United States has produced 54,000 pounds of ISS hardware; international partners have manufactured a total of more than 60,000 pounds of hardware. Boeing completes the main structure, Node 2, of the U.S. laboratory module.
October 18, 1995	The ESA Council meets in Toulouse, France, and approves the program "European Participation in the International Space Station Alpha," providing for the Columbus laboratory module, ATV, and studies of a European CTV.
December 1995	The Russian Space Agency announces that the Russian government owes Khrunichev money for work performed in 1995 and, if the government does not release the funds needed for the FGB and service module, it would be unable to meet the FGB's launch date and unable to build the service module.
January 1996	Exterior of the U.S. Station's modules is completed.
March 27, 1996	NASA Administrator Goldin states that he is giving Russia one month or six weeks to "get [the] Station moving again" and that he is "cautiously optimistic" that Russia will be able to "meet its commitment to deliver the critical service module on time…"[a]
May 1996	The ISS air purification system passes a major test of ability to control carbon dioxide, oxygen, and air pressure inside the Station's living and laboratory quarters.
November 1996	Node 1, the U.S. module, successfully completes the module's final pressure test.
December 1996	Russian FGB is assembled and ready for testing. The Russian Space Agency acknowledges that the service module will have to be delayed until December 1998 because of lack of funds.
January 1997	NASA allocates $100 million to Lockheed to develop the Interim Control Module as a backup to Russia's service module.

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Table 3–131. Space Station Chronology (Continued)

Date	Event
February 24, 1997	A fire on *Mir* endangers the crew.
April 1997	NASA and the Russian Space Agency formally agree to slip launch of the FGB from November 1997 to mid-1998.
April 9, 1997	NASA announces a slip in the Station's on-orbit assembly to "no later than" October 1998.
April 11,1997	Russia arranges for bank loans to Energia by the end of May, allowing work to resume on the service module.
May 15, 1997	The Space Station Control Board releases a new assembly schedule, Revision C. The FGB is scheduled to launch in June 1998, the U.S. node in July 1998, and the service module in December 1998.
May 31, 1997	The heads of space agencies accept Revision C at a meeting in Tokyo. Japan.
June 25, 1997	Collision between Progress cargo ship and *Mir* causes air leak and extensive damage.
June 1997	Node 1 (Unity) is shipped to Kennedy Space Center from Boeing plant in Alabama.
July 1997	Unpiloted, captive-carry flight tests of X-38 test airframes attached to B-52 aircraft begin at Dryden Flight Research Center.
September 1997	NASA and Boeing reveal that Boeing's prime contract will have at least a $600 million overrun at completion and that NASA needs $430 million more than expected for FY 1998.
September 1997	Goldin requests that the NASA Advisory Council establish a cost control task force.
September 1997	Revision C of the assembly and launch schedule is formally approved by all partners. The first U.S.-built element, Node 1, is scheduled to launch in July 1998, the Russian service module in December 1998, and the ESA's Columbus is scheduled to launch in October 2002.
September 18, 1997	The GAO releases a report describing worsening cost overruns.
October 14, 1997	NASA and the Brazilian Space Agency sign an implementing arrangement providing for the design, development, operation, and use of Brazilian-developed flight equipment and payloads for the ISS in exchange for Brazil's access to ISS facilities on orbit and a flight opportunity for a Brazilian astronaut.
November 1997	Boeing admits to a House panel that its costs are millions of dollars over its contract amount.
January 29, 1998	The United States and international partners sign a multilateral agreement formalizing the framework for cooperation among the ISS partners. Goldin also signs bilateral agreements with the heads of the ESA, the Canadian Space Agency, and the Russian Space Agency describing their roles and responsibilities. A similar agreement with the government of Japan is signed on February 24, 1998.

Table 3–131. Space Station Chronology (Continued)

Date	Event
March 12, 1998	First free-flight X-38 drop tests take place at Dryden Flight Research Center.
April 15, 1998	The Cost Control Task Force, chaired by Jay Chabrow, delivers its report to the Advisory Council. The report states that NASA will need an estimated $7 billion extra and up to three additional years to complete the program.
May 31, 1998	NASA's partners agree to officially target a November 1998 launch for the first Station component and to revise remaining launch dates. The partners set an April 1999 launch date for the service module and a summer 1999 date for transport of the first crew by Soyuz to the ISS.
June 15, 1998	The NASA response to the Cost Control Task Force report is released. NASA identifies $1.4 billion in additional costs. The schedule has been changed to accommodate a four-month service module schedule slip. The first element launch was moved to November 1998, and the ISS assembly complete date is scheduled for January 2004.
November 20, 1998	Launch of Zarya (FGB) takes place from the Baikonur Cosmodrome in Kazakhstan.
December 3, 1998	First U.S. component, Unity, is launched on STS-88.
December 6, 1998	Unity and Zarya dock.

[a] "Goldin Gives Russia Six Weeks To Get Station Moving Again," *Aerospace Daily* (March 27, 1996): Article 28066 (NASA History Office Folder 17083).

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CHAPTER FOUR

SPACE SCIENCE

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CHAPTER FOUR
SPACE SCIENCE

Introduction

The National Aeronautics and Space Act of 1958 directed NASA to contribute to the growth of human knowledge of Earth and space and to preserve America's role as a leader in space science and technology. Specifically, in the Declaration of Policy and Purpose, the Act stated, "The Congress declares that the general welfare and security of the United States require that adequate provisions be made for aeronautical and space activities." It next said, "The aeronautical and space activities of the United States shall be conducted so as to contribute materially to one or more of the following objectives: (1) the expansion of human knowledge of the Earth and of phenomena in the atmosphere and space; . . . (5) The preservation of the role of the United States as a leader in aeronautical and space science and technology and in the application thereof to the conduct of peaceful activities within and outside the atmosphere; . . . (7) Cooperation by the United States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results thereof . . . ."[1] In the years since NASA's birth, space science has continued to be a major focus of the Agency's programs.[2]

NASA launched 30 space science missions during the decade from 1989 through 1998, almost twice as many as during the previous decade. The majority were launched from ELVs, although five space science missions were deployed from the Space Shuttle during the decade. Several Space Shuttle missions carried on-board science payloads, and the crews conducted experiments as well as deployed and retrieved scientific satellites that flew freely in the vicinity of the Shuttle or carried out investigations while tethered to the Shuttle's robotic arm. In keeping with its mandate to cooperate with other nations and groups of nations, many of NASA's space science missions were international in scope, with NASA and other space agencies collaborating and sharing in the science investigations. In addition, NASA participated in space science missions launched by other countries and the DOD.

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[1] "Declaration of Policy and Purpose," *National Aeronautics and Space Act of 1958*, Public Law 85-568, 85th Congress, 2nd sess., July 29, 1958, as amended.

[2] Space science missions are typically those that look outward from an orbiting spacecraft into space, investigating the space environment, space phenomena, and the various objects in space. Earth science missions generally look toward Earth from orbit or examine the atmosphere surrounding Earth.

NASA's science missions were in the areas of astrophysics, space physics, interplanetary exploration, and solar physics. In addition, new technologies useful for space science missions were tested. Across all disciplines, these missions opened new vistas, adding immensely to the body of scientific knowledge about the cosmos and raising many new questions that remained to be investigated.

This chapter describes NASA's space science activities between 1989 and 1998. This chapter includes an overview of the decade and a brief summary of the previous decade's activities, budget data for the various programs, and a summary of the management structure and personnel. This chapter describes the individual missions launched during the decade, as well as those launched earlier but operated during this decade, and missions launched after 1998 but developed primarily by that year. For part of this decade, space science, Earth science, life sciences, and microgravity sciences were all included in one NASA administrative office. Only space science is addressed in this chapter. Earth science missions are included in chapter 2 of Volume VIII of the *NASA Historical Data Book*. Life sciences and microgravity sciences are included with human spaceflight in chapter 3 of this volume.

As is customary in these data books, most of the material in this chapter is based on primary NASA documents and Web-based materials produced by NASA. These include pre- and post-launch mission operation reports, press kits and press releases, key personnel announcements, and various reports and plans issued by the Agency. Where space science activities are Shuttle-based, the Space Shuttle mission archives and mission chronologies have been consulted. The NASA projects themselves have been plentiful sources of data. Most NASA projects have comprehensive Web sites, and many also publish information booklets and fact sheets. Partner agencies, such as the ESA, also publish printed and online material about their joint activities with NASA as do the academic and private-sector institutions and organizations that are the homes of researchers and investigators. Most budget material comes from the annual budget estimates generated by the NASA Office of the Chief Financial Officer and from federal budget legislation. Other government agencies and organizations including the GAO, Congressional Research Service, and NOAA also issue reports and documents used as reference material. Measurements are presented in the unit used in the original reference (metric or English); conversions are in parentheses.

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The Last Decade Reviewed

During the 10-year period from 1979 to 1988, NASA launched 17 space science missions, increasing our scientific understanding of the nature and processes of the universe by observing the distant universe, exploring the near universe, and investigating Earth's space environment. Missions included those sponsored by NASA's Office of Space Science (OSS) or Office of Space Science and Applications, those launched for other U.S. government agencies, and those involving international partners. Most space science missions were in the areas of planetary exploration, astrophysics, or solar terrestrial studies. The Life Sciences Division participated heavily in Spacelab missions and other investigations. In addition, scientists continued to receive and analyze data from earlier launches and prepare for future missions.

The decade began in 1979 with the "year of the planets" in space exploration. The Voyager and Pioneer planetary exploration missions revealed new information about Jupiter and its satellites; Saturn and Titan, its largest moon; Venus; and Mars. The encounter with the comet Giacobini-Zinner by the International Cometary Explorer (ICE) was the first mission of its type, carrying out on-site investigation of the comet. Researchers investigated astronomical x-ray sources using data obtained on the High Energy Astronomical Observatory (HEAO) mission, receiving the first high-resolution images of x-ray sources and detecting x-ray sources 1,000 times fainter than any previously observed and 10 million times fainter than the first x-ray stars observed.[3] They used data from the Solar Maximum Mission (SMM) to investigate solar activity in the Sun's energy output, output which probably contributed to climate change on Earth.

The *Challenger* accident in January 1986 delayed the launch of scheduled Space Shuttle missions. Astro-1, the Hubble Space Telescope, and the planetary missions Galileo and Ulysses were deferred to the beginning of the next decade. NASA returned to a "Mixed Fleet Strategy," remanifesting some of the other missions that had been scheduled for the Shuttle onto ELVs.

In addition to dedicated free-flying space science missions, almost all Space Shuttle missions performed scientific investigations on board. The first three Spacelab missions took place during the decade. Spacelab was the largest international cooperative space project undertaken to that time. The missions involved numerous disciplines, including atmospheric physics and Earth observations; space plasma physics; solar physics; materials science; life sciences; infrared astronomy; high-energy physics; and technology. Other on-board science experiments also were multidisciplinary.

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[3] "The Einstein Observatory (HEAO-2)," *http://heasarc.gsfc.nasa.gov/docs/einstein/heao2.html* (accessed May 8, 2006).

Space Science (1989–1998) Overview

During the 10-year period from 1989 to 1998, NASA launched 30 new space science missions (see Table 4–1). Five were launched from the Space Shuttle and the remainder from various ELVs. Eight missions focused on planetary investigations; 20 were physics and astronomy missions; and two were space science technology demonstrators, one with a significant planetary component. NASA also contributed an instrument to one Russian planetary mission, two Japanese missions, and partnered in a technology demonstration and space science DOD mission. Thirteen other space science missions were carried out on or near the Space Shuttle—as attached payloads, satellites flying freely near the Shuttle, or satellite servicing missions featuring ambitious spacewalks (see Table 4–2).[4]

These missions were highly productive and had an impressive success rate. Only one physics and astronomy mission, the dual HETE/SAC-B, failed entirely because of a launch vehicle malfunction, not because of an anomaly with the scientific payload. The planetary missions were less successful; three missions, all missions to Mars, failed. Among the attached and retrieved payloads, one deployment was unsuccessful and required a reflight. Many of the missions launched during the decade operated beyond their stated design life, and some were still operating in mid-2005. Some missions launched during the 1970s were still in use into the 1990s.

During the Agency's first two decades, NASA policy had called for a mixture of small explorers, medium-sized observatories, and large complex missions such as Viking and the Large Space Telescope to advance the state of technology and challenge the system. In the 1980s, the Agency moved toward an emphasis on large missions, reflecting the philosophy that it took as much time and energy to start a large mission as a small mission, and the science returns were greater.[5] As NASA's fourth decade began in 1989, it seemed as if the Agency would continue with large, complex, long-duration space science missions that characterized the program in the 1980s. Three major space science missions were approved between 1989 and 1991 while Richard Truly led the Agency: the Advanced X-ray Astronomical Facility (AXAF), the Comet Rendezvous-Asteroid Flyby (CRAF) mission, and a Saturn-bound mission named Cassini.[6] On October 4, 1989, President George H. W. Bush proclaimed the Space Exploration Initiative, an ambitious new mission to return to the Moon and then travel to Mars.[7] It quickly became clear that this initiative was too expensive in a time of increasing budget deficits and an ailing economy, and the initiative did not receive congressional support.

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[4] This adds to the Spacelab and SPACEHAB missions described in chapter 3, Human Spaceflight.

[5] John Naugle, comments to chapter 4, Space Science, December 24, 2005.

[6] John E. Naugle and John M. Logsdon, "Space Science: Origins, Evolution, and Organization," in John M. Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V: Exploring the Cosmos* (Washington, DC: National Aeronautics and Space Administration Special Publication 2001-4407, 2001), p. 14.

By the time Daniel Goldin replaced Truly in April 1992, cost overruns, delays, and failures of some larger missions were already contributing to the trend toward smaller, more frequent missions. The new Administrator, recognizing the need to rein in escalating costs, accelerated the trend and directed office administrators to plan for a level budget in the future rather than continued growth.[8] Within six months after joining NASA, Goldin introduced the Agency to the concept of "faster, better, cheaper" for future missions. The rationale was that undertaking more missions at lower costs and with shorter development times would produce better science results, allow more scientists the opportunity to participate in NASA missions, and allow for an occasional failure.[9] Although applicable to the entire Agency, the organization most affected by this new direction was the Office of Space Science and Applications.

The Agency introduced the Discovery Program later in 1992 to carry out Goldin's directive in the area of planetary exploration. Discovery Program missions were a series of less costly missions with specific scientific, technical, and programmatic guidelines. These small planetary missions had strict schedule, size, and cost limits and would complement larger missions and keep the scientific community involved with a steady stream of new planetary data.[10] The first Discovery mission, the NEAR mission, flew in 1997. The Mars Pathfinder and Lunar Prospector followed.

The Explorer program was also restructured during the decade, and a small Explorer component was added even before Goldin's tenure began. According to a NASA brochure, small Explorer satellites were designed to produce "extraordinary performance while fully embracing the essence of 'smaller, faster, cheaper.'"[11] All four small Explorer missions launched by 1998 succeeded.

NASA's space science programs fell into two large categories: 1) planetary or solar system exploration and 2) physics and astronomy. The first solar system exploration missions since 1978, Magellan and Galileo, had been victims of *Challenger*-induced launch delays. Launched in 1989, they were NASA's only two interplanetary launches in the 1980s. Upon arriving at Venus, Magellan embarked on a mission that yielded outstanding scientific results, revealing new information about the planet's surface. Galileo, despite a high-gain antenna that refused to unfurl, operated successfully and returned valuable scientific data on Jupiter and its moons.

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[7] W. Henry Lambright, "Transforming Government: Dan Goldin and the Remaking of NASA," Price Waterhouse, March 2001, pp.13–14.

[8] Committee on the Future of Space Science, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, *Managing the Space Sciences,* Chapter 3, The Changing Environment for Science at NASA, *http://www.nap.edu/html/ssb_html/Manage_Sp_Sci/fossch3.shtml* (accessed October 5, 2005).

[9] Naugle and Logsdon, p. 14.

[10] "Discovery Program Handbook," Document I-31 in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V,* p. 219.

[11] McCurdy, *Faster, Better, Cheaper,* p. 57.

The Mars missions of the 1990s had a mixed record. The Mars Observer, a scientifically ambitious and costly mission packed with expensive instruments, failed to regain contact with mission controllers after performing a maneuver to put it into orbit around Mars. In 1997, the relatively economical Mars Pathfinder mission demonstrated a less costly method of landing a spacecraft and science instruments on the Martian surface. The Pathfinder's small rover, named Sojourner, gathered an international following as it navigated the harsh Martian terrain. The Mars Global Surveyor also successfully reached Mars in 1997, conducting a successful mission. The next two Martian probes, the Mars Climate Orbiter and the Mars Polar Lander, failed. Both probes disappeared as they made their final approaches to the planet.[12]

One more planetary mission launched during the 1990s. The NEAR mission, the first of NASA's lower-cost Discovery missions, performed the first sustained examination of a near-Earth asteroid. The mission tested scientific theories on the formation of the solar system and management theories on cost reduction.[13]

NASA's physics and astronomy missions were in the areas of astrophysics, space physics, and solar physics; they ranged from large, complicated missions to small missions limited in scope. Two "Great Observatories" were launched during the decade. The first, the Hubble Space Telescope, launched in 1990, turned out to have blurred vision caused by spherical aberration introduced during manufacturing of the primary mirror. The telescope also had excessive jitter caused by expansion and contraction of the solar arrays related to temperature changes. The telescope's first servicing mission in 1993 installed corrective mirrors to sharpen the telescope's vision and replaced the solar arrays. This servicing mission was critical to regaining the Agency's credibility as well as the optical sensitivity that allowed the Hubble Space Telescope to produce the expected high-quality images.

The second Great Observatory, the CGRO, was one of several missions devoted to investigating gamma-ray bursts. The CGRO showed that gamma-ray bursts were evenly distributed over the sky. The mission was extremely productive, with investigations ranging from the solar system to distant regions of the universe. Another mission, the 1996 Italian-Dutch satellite, Beppo-SAX, launched on a U.S. launch vehicle from Cape Canaveral, Florida revealed that a gamma ray burst was followed by an optical image, permitting identification of the source.[14]

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[12] Amy Paige Snyder, "NASA and Planetary Exploration," in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V,* pp. 291–298.

[13] Howard McCurdy, *Low-Cost Innovation in Spaceflight: The Near Earth Asteroid Rendezvous (NEAR) Shoemaker Mission,* Monographs in Aerospace History no. 36 (Washington, DC: National Aeronautics and Space Administration Special Publication 2005-4536, 2005), p. 3.

[14] Nancy Grace Roman, "Exploring the Universe: Space-Based Astronomy and Astrophysics," in Logsdon, ed., *Exploring the Unknown, Vol. V,* pp. 515–516, 539.

NASA carried out several x-ray and UV studies during the decade, some with other countries. In 1982, NASA arranged to work with Germany and the United Kingdom on the ROSAT, an x-ray observatory launched in 1990 by the United States. NASA and the Massachusetts Institute of Technology (MIT) flew instruments on the Japanese ASCA. NASA's first satellite dedicated to the EUV, the EUVE was launched and operated until 2000 when NASA decided to deorbit the spacecraft because of budget constraints. The RXTE, the last large Explorer mission, continues to measure the variability over time in the emission of x-ray sources in a wide energy range. AXAF, renamed Chandra, launched in 1999 after 20 years of development.[15]

NASA launched several solar physics missions during this decade, beginning with Ulysses in 1990. This collaboration with the ESA produced a number of years of valuable heliospheric data as it flew over the solar poles. Another solar physics mission, the TRACE, a small Explorer mission with international participation and a "faster, better, cheaper" approach was developed in less than four years to refine knowledge of the relationship between solar magnetic fields and coronal heating. Launched on a U.S. launch vehicle, the SOHO (sometimes classified as a space physics rather than a solar physics mission) was an international mission built by the ESA carrying instruments from 14 countries and NASA. Despite battery difficulties, the SOHO sent back critical information about the Sun, contributing to the understanding of the Sun's internal dynamic structure and the onset of coronal bursts and mass ejections affecting solar-terrestrial relations.[16]

The discipline of space physics has been central to NASA's science program since discovery of what became known as the Van Allen belts in 1958. From 1989–1998, the ISTP and GGS programs formed the framework for a number of space physics missions, including NASA's Wind and Polar spacecraft, the ESA's SOHO and Cluster spacecraft, and Japan's Geotail spacecraft. The NASA portion of the CRRES, a joint NASA-U.S. Air Force mission, also was planned to be part of the ISTP program.

NASA's space physics program benefited from the Explorer program restructuring, which called for launching two Explorer missions per year and included a Principal Investigator (PI)-mode, a mode in which the PI took full responsibility for all aspects of the mission. A number of small, focused science missions complemented NASA's GGS program. Between 1989 and 1998, these missions included the SAMPEX, launched in 1992; the FAST, launched in 1996; the ACE, launched in 1997; and TRACE (a solar physics mission), launched in 1998.[17]

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[15] Roman in Logsdon, ed. pp. 517–521, 540.

[16] David H. DeVorkin, "Solar Physics from Space," in John M. Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume VI: Space and Earth Science* (Washington, DC: National Aeronautics and Space Administration Special Publication 2004-4407, 2004), pp. 35–36.

[17] James Green and Brian Dewhurst, "Space Physics," in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume VI*, pp. 157, 168–173.

At the close of the decade, a new concept was introduced in which space physics missions would perform the scientific research necessary to support a variety of practical applications relating to space weather and its effect on human society and life. Named Living With a Star, the initiative, under the leadership of George Withbroe, added a practical dimension to the traditional rationale for space science: increase understanding and apply that understanding in useful ways. The initiative focused on human radiation exposure related to spaceflight and high-altitude flight; the impact on space assets; satellite operations; communication systems; terrestrial power grids; and the effects of solar variability on terrestrial climate change. Supported by Goldin, it was presented to the Clinton administration as an "add-on" to the FY 2001 budget, where it became a NASA initiative in FY 2001.[18]

Management of NASA's Space Science Program

The organizational structure and responsibilities of NASA's space science program office are similar to those found in program offices throughout the Agency.[19] The OSSA (or the OSS later in the decade) was headed by an Associate Administrator, located at NASA Headquarters, who was responsible for "the overall planning, direction, execution, and evaluation of the NASA programs concerned with space science . . ." The Associate Administrator also had institutional management of NASA's Goddard Space Flight Center and the Jet Propulsion Laboratory.[20] These NASA Centers were the "lead centers" for the Agency's space science missions and the location of the missions' project offices with responsibility for mission implementation.

The heads of several discipline areas or programs, usually called divisions, reported to the Associate Administrator. These program areas changed over time but generally included the areas of physics, astronomy, and planetary exploration. Each division was responsible for specific scientific missions consisting of one or more spacecraft, instruments, and a number of scientific experiments. A PI was responsible for each instrument and for analyzing and publishing data from the instrument. The PI also was responsible for placing the data in a data center accessible to other scientists.

In most cases, the project office at the lead Center was responsible for the design and development or procurement of the mission's hardware as well as testing the hardware, integrating it with the launch vehicle, operating the spacecraft, and delivering the data to the PI.[21] The project manager headed the project office, and the project scientist was usually collocated in the project

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[18] Green and Dewhurst in Logsdon, pp. 174–175.

[19] Midway during this decade, NASA moved from a program office structure to a strategic enterprise structure, headed by an Enterprise Associate Administrator.

[20] *NASA Management Instruction 1102.1H,* "Role and Responsibilities–Associate Administrator for Space Science and Applications," July 30, 1992.

[21] John Naugle, comments to chapter 4, Space Science, December 24, 2005.

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office and the science directorate at the project's lead Center. International missions, and missions managed jointly with other U.S. agencies, might have different arrangements.

At the beginning of the 1989–1998 decade, the OSSA managed space science missions, referred to within NASA as Code E. This combined organization had been established in November 1981. The divisions within OSSA relating to space science were Space Physics, Solar System Exploration, and Astrophysics (see figure 4–1). The remaining divisions not involved with space science were Space Earth Sciences and Applications, Microgravity Science and Applications, Communications and Information Systems, and Life Sciences. Lennard A. Fisk was Associate Administrator of the OSSA; Stanley Shawhan headed the Space Physics Division; Geoffrey Briggs headed the Solar System Exploration Division; and Charles J. Pellerin headed the Astrophysics Division.

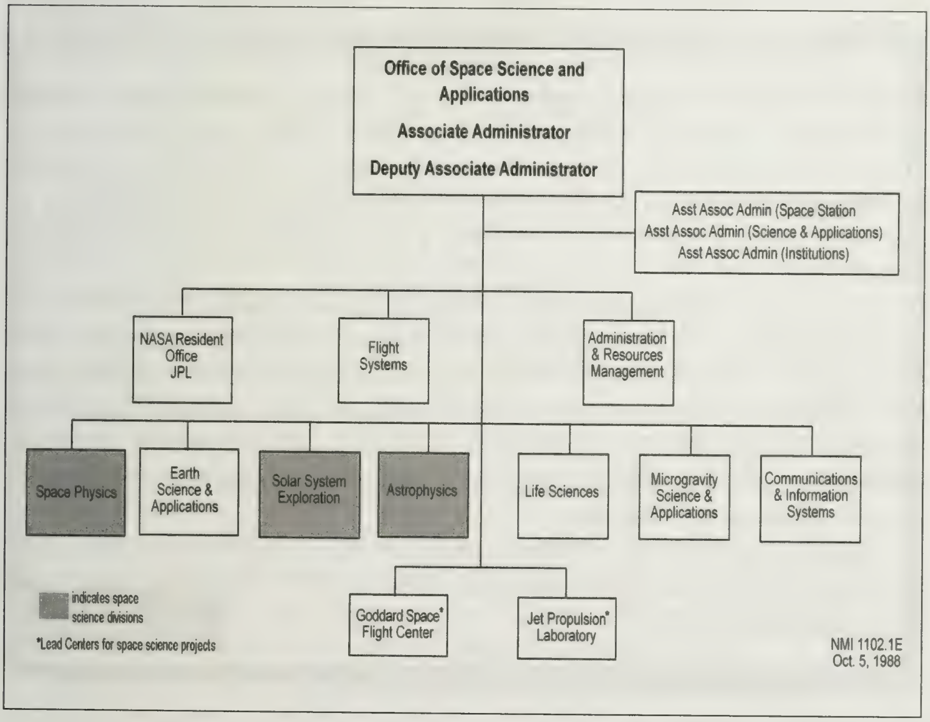
Office of Space Science and Applications
Associate Administrator
Deputy Associate Administrator
Asst Assoc Admin (Space Station
Asst Assoc Admin (Science & Applications)
Asst Assoc Admin (Institutions)
NASA Resident Office JPL
Flight Systems
Administration & Resources Management
Space Physics
Earth Science & Applications
Solar System Exploration
Astrophysics
Life Sciences
Microgravity Science & Applications
Communications & Information Systems
Goddard Space* Flight Center
Jet Propulsion* Laboratory
▨ indicates space science divisions
*Lead Centers for space science projects
NMI 1102.1E
Oct. 5, 1988

Figure 4–1. Office of Space Science and Applications, 1981–1993

In April 1990, an administrative action changed the letter designation for OSSA to Code S, but the functions and organization remained the same. In June 1990, Shawhan died of a sudden heart attack. His deputy, Thomas Perry, became acting Director of the Space Physics Division.[22] In July 1990, Wesley Huntress, Jr., replaced Briggs as head of the Solar System Exploration Division. In spring 1991, George L. Withbroe became Director of the Space Physics Division.

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[22] George Withbroe, e-mail to author, October 3, 2005.

In July 1992, the roles and responsibilities assigned to the OSSA changed to include responsibility for "planning, development, and operation of NASA missions that used the Space Shuttle, Spacelab, other Shuttle-attached payload carriers, and Space Station *Freedom* . . . " The OSSA also assumed responsibility for managing and directing the ELV and upper stages launch service program, including "planning, requirements, acquisition strategy, operations, and oversight . . . ."[23]

In October 1992, Administrator Goldin announced an Agency-wide reorganization to "better focus NASA's programs, to streamline how we do business so we can meet the challenges ahead" that affected the management of space science missions.[24] The OSSA split into two organizations, one to manage space science missions and the second to manage Earth science and applications missions. The temporarily renamed Office of Planetary Science and Astrophysics (Code S) managed space science missions. Applications missions went to the new Mission to Planet Earth (Code Y) office. At the time, neither life sciences nor microgravity science was mentioned.[25] Huntress became acting Associate Administrator of the reconfigured space science organization, replacing Fisk, who did not agree with the Administrator's "faster, better, cheaper" policy and was reassigned to the position of Agency Chief Scientist.[26] William L. Piotrowski replaced Huntress as acting head of the Solar System Exploration Division. These changes became effective in March 1993.

At the same time, the OLMSA (Code U) was established. This office was formed from the offices within the old OSSA that dealt with life sciences and microgravity.[27] Before the end of the month, the Office of Planetary Sciences and Astrophysics changed its name to the simpler OSS. Activities previously managed by the Office of Exploration, headed by Michael Griffin, were also absorbed by the OSS, and the Exploration Office was disbanded.[28] See Figure 4–2 for the new OSS structure.

Pellerin left as head of the Astrophysics Division in June 1993. The position remained vacant until April 1994 when Daniel Weedman was appointed to the position.

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[23] NASA Management Instruction 1102.1H "Role and Responsibilities–Associate Administrator for Space Science and Applications," (July 30, 1992).

[24] "Goldin Announces Changes in NASA Organization To Focus and Strengthen Programs and Management," *NASA News* Release 92-172, October 15, 1992, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1992/92-172.txt* (accessed April 18, 2006).

[25] Committee on the Future of Space Science, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, *Managing the Space Sciences*, chapter 1, Introduction, *http://www.nap.edu/html/ssb_html/Manage_Sp_Sci/fossch1.shtml* (accessed October 5, 2005).

[26] John Naugle, comments to chapter 4, Space Science, December 24, 2005.

[27] "Assignment of Key Personnel and Establishment of New Offices," NASA Special Announcement, March 11, 1993. OLMSA is discussed in chapter 3.

[28] "Exploration Effort Shifted to Office of Space Science," *NASA News* Release 93-54, March 25, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-054.txt* (accessed July 9, 2005).

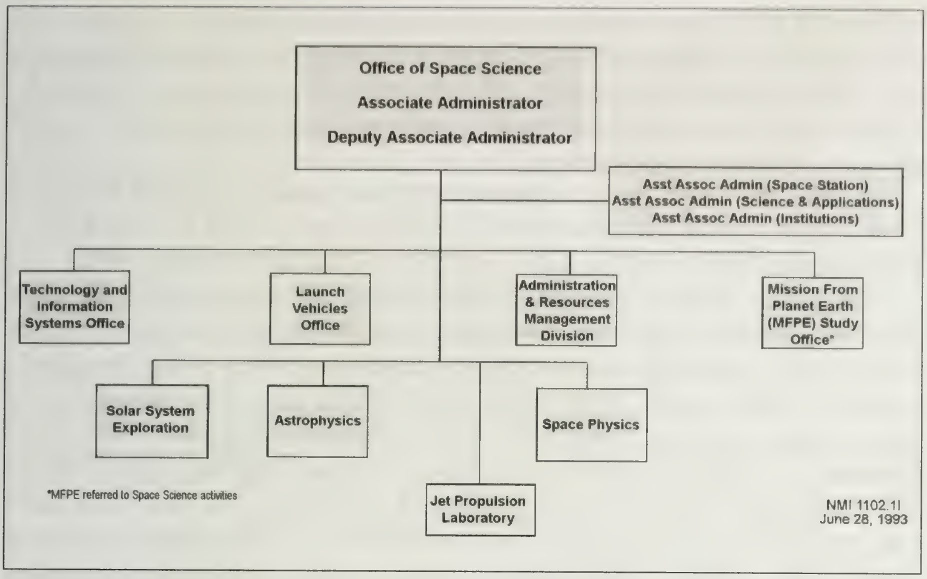
Office of Space Science
Associate Administrator
Deputy Associate Administrator
Asst Assoc Admin (Space Station)
Asst Assoc Admin (Science & Applications)
Asst Assoc Admin (Institutions)
Technology and Information Systems Office
Launch Vehicles Office
Administration & Resources Management Division
Mission From Planet Earth (MFPE) Study Office*
Solar System Exploration
Astrophysics
Space Physics
Jet Propulsion Laboratory
*MFPE referred to Space Science activities
NMI 1102.1I
June 28, 1993

Figure 4–2. Office of Space Science (1993)

In September 1994, the OSS published the Office of Space Science Strategic Plan for 1995–2000. The vision of space science, as stated in the plan, was to "explore and seek to understand the Sun, the Solar System, the Galaxy, and the Universe, for the benefit of humanity."[29] The plan identified four central science themes: the Galaxy and the Universe, the Sun-Earth-Heliosphere Connection, Planetary System Origin and Evolution, and Origin and Distribution of Life in the Universe. Each theme had intellectual questions that current and future projects sought to answer and strategies for accomplishing near-term and long-term objectives relating to the theme. Each program, whether currently operating, in development, or planned for the future, was identified with one or more themes. The plan recognized that declining budget expectations for space science required a different approach for future missions, using smaller spacecraft and new technologies to reduce spacecraft development and launch costs and to distribute risk.

In the spring of 1995, NASA again took steps to reduce costs and increase organizational efficiency. The Agency released a new Strategic Plan in May 1995 with five "strategic enterprises" forming the framework for strategic planning at NASA. OSS projects and research programs were in the Space Science Enterprise. At the same time, a key decision was made to assign each field Center a clearly defined primary mission, structured along a series of strategic enterprises and functional responsibilities. "Centers of Excellence" for each discipline area already existed, with missions in particular disciplines managed by Centers with specific expertise. This step formalized the process.

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[29] National Aeronautics and Space Administration Office of Space Science, *Space Science for the 21st Century: Strategic Plan for 1995–2000*, September 1994.

In the area of space science, two Centers were involved. The “mission” of Goddard Space Flight Center, the Center of Excellence for scientific research, was Earth science and physics and astronomy. The “mission” of the Jet Propulsion Laboratory, the Center of Excellence for deep space systems, was planetary science and exploration.[30]

Around the same time, Jurgen Rahe was appointed to head the Solar System Exploration Division, which Piotrowski had led on an acting basis. Rahe led the division for two years, until his sudden death in June 1997.

Six months later, in November 1995, Goldin again reorganized the OSS. Associate Administrator Huntress stated in a memo that the changes were made to “meet the drastically reduced staffing levels prescribed in the President’s initiative, while preserving both the excellence in managing NASA’s space science program and its strong bond with the science community.”[31] He listed four science themes: Galaxy and Universe, Astronomical Search for Origins and Planetary Systems, Solar System Exploration, and the Sun-Earth Connection. These four themes were almost identical to those introduced a year earlier in the Office of Space Science Strategic Plan. The existing discipline divisions and their branches within the OSS transformed into programs corresponding to these themes. The programs were led by program directors who provided an integrated scientific perspective for each theme and collectively functioned much like a chief scientist for the OSS.[32] Space Physics became the Sun-Earth Connection, still headed by Withbroe. Solar System Exploration kept the same name, with Jurgen Rahe as the head. Weedman left the disbanded Astrophysics Division, which was restructured into two programs: the Astronomical Search for Origins and Planetary Systems, led by Edward J. Weiler, former chief of the Ultraviolet and Visible Astrophysics Branch; and Structure and Evolution of the Universe, led by Alan Bunner, former chief of the High Energy Astrophysics Branch.[33] With the abolishment of the discipline divisions and their associated branches while their functions moved to the Goddard Space Flight Center or Jet Propulsion Laboratory, space science staffing at NASA Headquarters was reduced from more than 200 civil servants to less than 70 persons.[34]

As well as the thematic programs, the restructured OSS had the following three functionally oriented operating divisions: Research Program Management, led by Henry Brinton, housed all the program scientists and was where scientific research was accomplished, fundamental questions defined, measurements required from the space missions specified, and data analyzed.

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[30] “Review Team Proposes Sweeping Management, Organizational Changes at NASA,” *NASA News* Release 95-72, May 19, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-73.txt* (accessed April 25, 2005).

[31] Wesley Huntress, Jr., to multiple addresses, “NHB 1101.3 NASA Organization Handbook,” November 9, 1995.

[32] George Withbroe, e-mail to author, October 3, 2005.

[33] Weedman left NASA and returned to a faculty position at Pennsylvania State University.

[34] Green and Dewhurst, “Space Physics,” in Logsdon, p. 174.

Advanced Technology and Mission Studies, led by Peter Ulrich, was where the tools to carry out the space missions were developed and tested. The Mission and Payload Development Division, led by Kenneth Ledbetter, was where flight missions were developed. The Mission and Payload Development Division housed all of the engineers and program managers. Figure 4–3 shows the new structure.

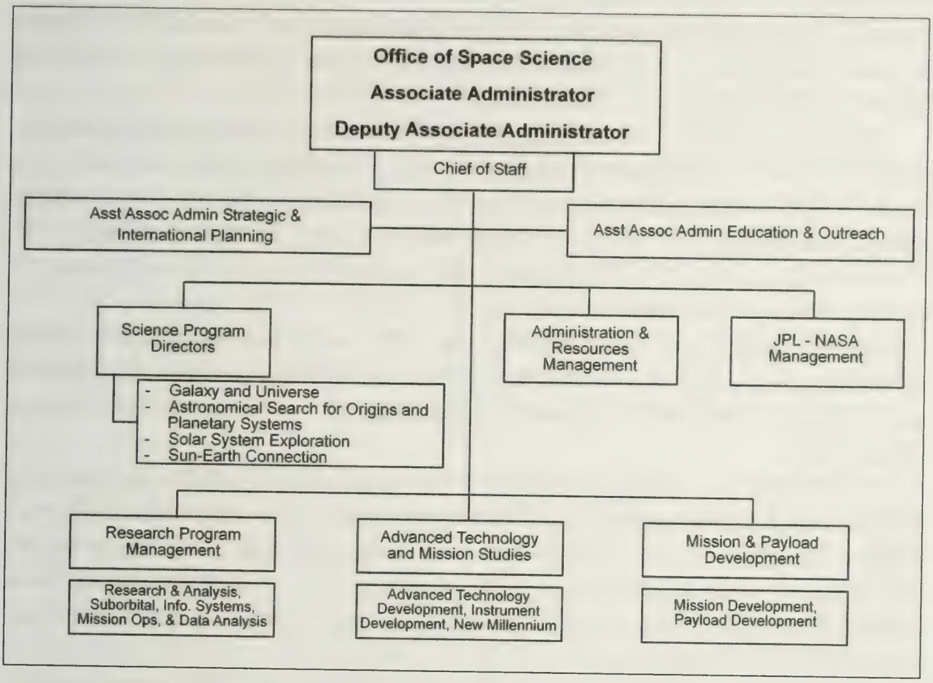
Office of Space Science
Associate Administrator
Deputy Associate Administrator
Chief of Staff
Asst Assoc Admin Strategic & International Planning
Asst Assoc Admin Education & Outreach
Science Program Directors
- Galaxy and Universe
- Astronomical Search for Origins and Planetary Systems
- Solar System Exploration
- Sun-Earth Connection
Administration & Resources Management
JPL - NASA Management
Research Program Management
Research & Analysis, Suborbital, Info. Systems, Mission Ops, & Data Analysis
Advanced Technology and Mission Studies
Advanced Technology Development, Instrument Development, New Millennium
Mission & Payload Development
Mission Development, Payload Development

Figure 4–3. Office of Space Science (November 1995)

Carl Pilcher, Office of Space Science Assistant Associate Administrator for strategic and international planning, assumed the position of acting head of the Solar System Exploration Division upon the death of Rahe in 1997 and became head in 1998.

In February 1998, Huntress announced that he would leave NASA. In November, Weiler, who had served as acting OSS Associate Administrator since September 28 and led the Astronomical Search for Origins and Planetary Systems program, was appointed to the position.

Money for Space Science

The R&D appropriation through FY 1994 and the SAT appropriation beginning in FY 1995 funded NASA's space science activities. From FY 1989 to FY 1996, NASA's space science funds were divided into the following two major discipline categories within the broader space science category:[35] 1)

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[35] Funding associated with Life Sciences can be found in chapter 3, Human Space Flight.

Physics and Astronomy, and 2) Planetary Exploration. Each of these discipline categories funded every mission under development in the discipline, mission operations and data analysis for missions that had been launched and were operational, and research and analysis. More specifically, mission operations and data analysis funded in-flight operation of spacecraft and the analysis of data from those missions. Research and analysis funds ensured that data and samples returned from flight missions were fully exploited; undertook complementary laboratory and theoretical efforts; defined the science rationale; and developed the technology needed to undertake future missions.

To fund a space science program, the director of the proposed program first defended the program to the space science Associate Administrator, then to the NASA Administrator, and finally to the OMB as part of the annual budget submission. The OMB then submits the President's budget to Congress for approval. A description of the budget process is in chapter 1, Introduction, of this data book.

In FY 1993, NASA restructured the OSS and moved programs dealing with life sciences to a new program office, the OLMSA. The new structure was reflected in the FY 1994 budget request (see chapter 3, Human Spaceflight).

In FY 1997, the OSS combined its Physics and Astronomy and Planetary Exploration budget categories and listed all projects in a single Space Science budget category. In the Space Science budget category, missions under development were still listed separately by name but with only one mission operations and data analysis budget category and one research and analysis budget category rather than two (as in previous years).

Also beginning with the FY 1997 budget request, NASA started moving toward implementing "full-cost accounting," a method in which all costs associated with a project were included in the project budget. Starting with projected FY 1997 costs, NASA showed budget figures using both the traditional method (being phased out) and the new "full-cost" method, shown as "budget authority," or the amount appropriated by Congress.[36] FY 1995 and the prior years' budget authority were recalculations reflecting the full cost of all elements associated with a project. For space science missions, the full cost of a mission typically included costs for development of the spacecraft and experiments, postlaunch mission operations and data analysis, launch support, and tracking and data acquisition support.[37] Previously, only the development cost was associated with a mission budget, and it was necessary to search for the costs for mission operations, launch, and tracking in other parts of the budget and determine the amounts applicable to a particular mission. In the following tables where an amount for "budget authority" is shown, the phasing of both actual costs and projected budget authority come from the FY 1998 Budget Estimate. Phasing of funds may have been somewhat different in the FY 1997 Budget Estimate and earlier, but the final cost to complete a project would have been roughly the same. Also, the full-cost figures stated here do not include amounts contributed by international participants or costs for the use of non-program-unique government facilities and general and administrative support used to carry out research and development activities or for early definition phase activities.

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[36] Budget authority represents the amounts appropriated by Congress in a given fiscal year that provide NASA with the authority to obligate funds. Obligation of funds legally commits NASA to pay contractors and other service providers for materials and services. The ensuing obligations, cost incurrence, and expenditures (outlays) based on the budget authority can occur in a different fiscal year from the year in which Congress provides the budget authority.

[37] The cost of civil service labor is not included in these figures, although it would be included in complete "full-cost" figures.

From 1989–1998, NASA's Space Science budget generally rose, although typically at a modest pace, usually barely outpacing the rate of inflation. In FY 1991, the amount Congress authorized for space science did not exceed the rate of inflation, and in FY 1998, the amount for space science fell.[38] Starting with the FY 1993 budget and continuing for three years, the amount authorized for physics and astronomy missions also fell. However, the amount authorized for planetary missions rose significantly during the same period, and the total amount for space science missions increased until FY 1998 (see Table 4–3).

For most of the decade, the programmed amounts (reflecting what NASA actually had available to spend) increased (see Table 4–4). In 7 of 10 years, the programmed budget for space science activities grew less than 10 percent but still more than the rate of inflation. In FY 1991, the programmed amount grew slightly more than 15 percent, capping a three-year period in which three large programs were approved. In FY 1994, the programmed budget increased 27 percent over the prior year. The programmed amount dropped in the following two years: FY 1993 by 3.8 percent, reflecting an effort by the administration to reduce the federal deficit, and FY 1997, by 9.4 percent. However, in FY 1994, a 27.1 percent increase made up for the decrease of the prior year. The modest 3.8 percent increase in FY 1998, however, did not cover the drop of the previous year, increasing the budget to only slightly more than the FY 1995 level.

Beginning in 1992, the Agency implemented Daniel Goldin's "faster, better, cheaper" approach. The Discovery Program, New Millennium Program, Mars Surveyor Program, Small Explorer Program, and Small Satellite Technology Initiative sponsored a greater number of smaller, more frequent projects.[39] The Agency also reduced costs through greater international cooperation on new flight programs, involving the space agencies of other countries as full partners that contributed instruments and other key components as well as sharing in the science results. The number of missions NASA successfully flew during this decade and the wide range of scientific discoveries made in diverse disciplines demonstrated the success of this approach.

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[38] In most years, annual appropriations legislation did not designate an amount specifically for space science. The authorization bill and committee proceedings provided guidance as to Congress's intent and formed the basis for the Agency's annual operating plan. An authorization act authorizes the enactment of appropriations and specifies how appropriated funds are to be used. In some years, no authorization bill was passed. The annual appropriations act provides funds for federal agencies to make payments out of the Treasury for specified purposes. In years when there was an authorization act, the act's text was typically more specific than in the appropriations act, which provides direction for only major budget appropriations categories (U.S. Senate Glossary), *http://www.senate.gov/pagelayout/reference/b_three_sections_with_teasers/glossary.htm* (accessed July 14, 2006).

Tables 4–5 to 4–35 show budget requests and programmed amounts for the programs in space science. If Congress indicated an authorized amount for a program, that amount is indicated.[40] Since NASA typically submits an original and revised budget request before Congress acts on a budget, both amounts are indicated and separated by a forward slash. Where no amount appears, there was no submission. Programmed amounts are determined after the end of a fiscal year and reflect the amounts actually available to be spent. Occasionally, a budget category was established during a fiscal year. When that happened, there is a programmed amount shown but no budget request for that activity. Funds for these introduced activities generally were taken out of another project's budget through a "reprogramming" of funds. All amounts stated come from the annual budget requests prepared by the NASA Office of the Chief Financial Officer.

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Space Science Missions

Overview

NASA's space science missions fit into the following three discipline areas: space physics, astrophysics, and solar system exploration. During the first part of the decade, three corresponding divisions managed these discipline areas. The Space Physics Division supported investigations into the origin, evolution, and interactions of particulate matter and electromagnetic fields in a wide variety of space plasmas. Missions managed by this division studied the upper atmospheres, ionospheres, and magnetospheres of Earth and other planets; the Sun as a star and as a source of solar system energy, plasma, and energetic particles; and the acceleration, transport, and interactions of energetic particles and plasmas throughout the solar system and the galaxy. Observations, theory, modeling, simulations, laboratory studies, interactive data analysis, instrument development, and active experiments were aspects of the Space Physics program. The division included research programs in ionospheric, magnetospheric, solar, and cosmic and heliospheric physics. The Suborbital Research program was also part of the Space Physics Division.

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[39] Small Satellite Technology Initiative projects fell into the category of space applications and are addressed in the Space Applications chapter in Volume VIII of the *NASA Historical Data Book*.

[40] Usually Congress stated authorized amounts only for major budget categories or programs of great visibility.

Missions managed by the Astrophysics Division studied the origin and evolution of the universe, the fundamental physical laws of nature, and the birth of stars, planets, and ultimately life. Because these subjects required some observations at wavelengths absorbed by Earth's atmosphere, observations needed to take place from space-borne instruments. This program centered on the four Great Observatories; a series of smaller spacecraft; and suborbital rockets, balloons, and aircraft. The Great Observatories—the Hubble Space Telescope, GRO, AXAF, and SIRTF—each provided significantly improved sensitivity and resolution over their selected region of the electromagnetic spectrum. The Explorer spacecraft performed exploratory work, all-sky surveys, specific studies, and unique investigations not suited to the Great Observatories. Suborbital vehicles provided the means to make preliminary observations, conduct selected investigations at lower cost, test instrumental concepts, and nurture groups capable of developing instruments for future space missions.

The Solar System Division was responsible for all of NASA's deep space missions and for the exploration of all the planets and other solar system constituents such as asteroids, comets, and the interplanetary medium.[41] This division's investigations included the search for planetary systems around other stars, conducting comparative planetary studies, and establishing the scientific and technical database required to support major human activities on other planets.[42]

In 1995, NASA gave its space science organization a more multidisciplinary focus. For funding purposes, however, NASA's space science missions remained in two categories: physics and astronomy, which encompassed both space physics and astrophysics missions as well as planetary exploration. Missions addressed in this chapter are arranged in these two categories.

The descriptions of missions in this chapter launched during the decade 1989–1998 include both narrative material and mission tables. If the mission continued to operate past 1998, it is noted in the table; but most events occurring after 1998 are not described. If a mission launched before 1989 but continued to operate into the decade addressed here, the description focuses on events beginning in 1989. When mission development occurred primarily between 1989 and 1998 but the mission did not launch until after 1998, events occurring through 1998 are addressed.

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[41] "Guide to NASA's Office of Space Science & Applications," prepared by the NASA Headquarters Office of Communications, Office of Space Science and Applications Public Affairs Office, July 5, 1988.

[42] Office of Space Science and Applications, *Strategic Plan 1991,* p. 7 (NASA History Office Folder 18431).

Role of the Principal Investigator

Typically, NASA's space science missions draw heavily on the participation and contributions of their PIs. These scientists, who often work with teams of researchers of varying sizes, come from NASA, other U.S. and foreign agencies, academia, research organizations, and the private sector. The PI frequently participates in instrument development and the determination of science objectives and is responsible for the instrument's calibration before launch and for much of the science program after launch.

During the 1990s, NASA shifted the degree of PI responsibility. On older space science missions, PIs took responsibility for the science instruments and data analysis with NASA managing the project and developing the spacecraft. Beginning in the mid-1990s, NASA moved toward missions offering scientists the opportunity to lead their own space science missions, termed PI-led missions.[43] A mission characterized as PI-led "entrusts the scientific, technical, and fiscal management to a single PI and his or her teams. The PI has responsibility for defining the mission concept and controlling its cost, schedule, and targeted scientific investigation."[44] PI-led missions differ from NASA's "core" missions, which are defined in NASA's strategic plans, because the scientist's involvement in a core mission occurs first when defining the mission, then as a competitively selected instrument provider, and then during data analysis and interpretation. Also, in a core mission, NASA usually takes responsibility for the spacecraft and often provides significant help with the experiment.[45] PI-led missions, on the other hand, are conceived and promoted by smaller groups in the scientific and technical communities to carry out space-based measurements that core missions do not cover. On a PI-led mission, PIs choose and organize their implementation team and decide how best to use project resources to accomplish the mission's scientific goals. In general, PI-led missions include the following:

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- Operate under a cost cap.
- Are led by a single PI affiliated with a range of possible types of institutions.
- Designate the PI responsible for *all* aspects of the mission, including development, management, risk management, and termination if the science objectives are no longer likely to be met within cost and schedule reserves.
- Allow the PI control over organizational and management specifics with "only essential NASA oversight."[46]

Examples of PI-led missions include some Explorer missions and missions in NASA's Discovery Program.[47]

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[43] Committee on Principal-Investigator-Led Missions in the Space Sciences, Space Studies Board Division on Engineering and Physical Sciences, National Research Council, *Principal-Investigator-Led Missions in the Space Sciences* (Washington, DC: The National Academies Press, 2006), p. 1 (PDF available at ***http://darwin.nap.edu/books/0309100704/html/***) (accessed May 5, 2006).

[44] *Principal-Investigator-Led Missions in the Space Sciences,* pp. 10–11.

[45] Nancy Roman, e-mail to author May 20, 2006.

[46] *Principal-Investigator-Led Missions in the Space Sciences*, p. 91.

[47] *Principal-Investigator-Led Missions in the Space Sciences*, pp. 16–17.

Physics and Astronomy Missions

Space science missions funded by the Physics and Astronomy program included the Explorer missions, the Great Observatories, a series of smaller spacecraft, and suborbital balloons and rockets.

Explorers Program

NASA's Explorers Program provided frequent, less costly access to space for physics and astronomy investigations that could be accommodated with small to midsized spacecraft. The program supported investigations in all space physics and astrophysics disciplines that were usually of an exploratory or survey nature or had specific objectives not requiring the capabilities of a major observatory. Since the first Explorer launch in 1958, Explorer missions have discovered radiation trapped within Earth's magnetic field, investigated the solar wind and its interaction with Earth, studied upper atmosphere dynamics and chemistry, mapped our galaxy in radio waves and gamma rays, and determined properties of the interstellar medium through UV observations.[48] The missions also have performed active plasma experiments on the magnetosphere, made *in situ* measurements of the comet Giacobini-Zinner, and completed the first high sensitivity, all-sky survey in infrared, discovering more than 300,000 sources.[49] The Explorers Program also helped develop instruments for "payload-of-opportunity" missions, such as those involving other federal agencies or international collaboration.

In 1988, the Explorers Program began developing a group of "small class" explorers. These Small Explorer missions, called SMEX, provided frequent flight opportunities for highly focused and relatively inexpensive space science missions in the disciplines of astrophysics and space physics. The program conducted focused investigations probing conditions in unique parts of space, complementing major missions, proving new scientific concepts, and making other significant contributions to space science. The first three SMEX missions, selected from 51 candidates, were announced on April 4, 1989. The SAMPEX missions launched in 1992; the FAST launched in 1996; and the SWAS launched in 1998. All of these missions studied important questions in space physics, astrophysics, and upper atmosphere science.

The second SMEX mission set, announced on September 14, 1994, chose two science missions. The first of the newly selected missions, the TRACE, observed the Sun to study the connection between its magnetic fields and the heating of the Sun's corona. The TRACE launched in April 1998. The second spacecraft, the Wide-Field Infrared Explorer (WIRE), launched in 1999 to study the evolution of galaxies using a cryogenically cooled telescope and arrays of highly sensitive infrared detectors for the studies.

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[48] Riccardo Giacconi received the Nobel Prize in large part because of research he did with the first Explorer, Uhuru. (John Naugle)

[49] "Explorer Development," Office of Space Science and Applications, Research and Development Fiscal Year 1992 Estimates, Budget Summary, p. RD-3-17.

Unlike larger missions, SMEX team members worked on more than one mission at a time. SMEX missions overlapped and staggered their schedules so that the program launched a satellite every one to one and one-half years. Development typically took approximately three and one-half years. The program was structured to accept increased risk, reduce costs, and increase the flight rate. By having a short development time, SMEX missions also provided training opportunities for the next generation of scientists and engineers. The Engineering Directorate at Goddard Space Flight Center managed the SMEX program.[50]

In the mid-1990s, to enable more frequent flights, NASA initiated the Medium-class Explorer (MIDEX) program. MIDEX missions were larger than SMEX missions but smaller and less expensive than Delta-class missions. They were to be launched aboard a new Med-Lite class launch vehicle. This new launch vehicle was not developed, however, and the first mission intended for this program, the Far Ultraviolet Spectroscopy Explorer (FUSE), launched on a Delta II in 1999. NASA chose the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) and Microwave Anisotropy Probe (MAP) in 1996 as MIDEX missions. IMAGE launched in 2000 and MAP in 2001, both on Delta IIs.

The STEDI Program was a three-year pilot program under the Explorer umbrella that aimed to demonstrate that high-quality space science and technology missions could be carried out with small, less costly, free-flying satellites on a timescale of two years from go-ahead to launch. The STEDI program hoped to make science in orbit available to universities and other small users for research, graduate education, and training of entry-level professionals.

The STEDI announcement of opportunity was released on May 12, 1994, and 66 proposals were received in response. Six of these were selected for further study and development. In February 1995, two of these projects, the Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources (TERRIERS), led by Boston University, and the SNOE, led by the University of Colorado, were chosen for fully funded flight development. A third project led by the University of New Hampshire, the Cooperative Astrophysics and Technology Satellite (CATSAT), was selected as an alternate. In 1996, additional funding was secured to fully fund the CATSAT mission.

Each of the three teams received about $4.5 million to cover design, manufacture, and one full year of science operations. Launch procured under the NASA Ultralite Expendable Launch Vehicle procurement was provided on an Orbital Sciences Pegasus XL rocket. The STEDI spacecraft were dual manifested as the primary payload—Orbital had the option of booking a secondary payload. Following launch to low Earth orbit (550 kilometers), the

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[50] "SMEX Project History," *http://sunland.gsfc.nasa.gov/smex/history/miss1.html* (accessed September 27, 2005).

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missions would collect data for up to one year.[51] SNOE launched in 1998; TERRIERS in 1999. CATSAT did not launch because no launch vehicle was available. The STEDI program was terminated in 2001.[52]

Although not an Explorer mission, the Explorers Program provided the U.S. instrument flown on the ROSAT, a U.S.-German cooperative mission conducting the first detailed all-sky x-ray survey and performing in-depth studies of selected objects. The program also managed the CRRES, a joint NASA-DOD mission launched into geosynchronous orbit that released trace chemicals whose transport in the magnetosphere could be observed from ground-based and airborne instruments. Explorer missions launched during 1989–1998 are listed in Table 4–36.

Cosmic Background Explorer

Goddard Space Flight Center developed the COBE to investigate the origin and dynamics of the universe, including the theory that the universe began about 15 billion years ago with a cataclysmic explosion—the Big Bang. COBE mission activities included a definitive exploration and study of the diffuse radiation of the universe between the wavelengths of 1 micrometer and 9.6 millimeters. This region included the 3 K (-270°C) cosmic background radiation, the residual radiation from the Big Bang presumed to have started the expansion of the universe, and also included the 1-micrometer to 300-micrometer infrared region.[53]

The spacecraft was launched November 18, 1989. It comprised an instrument module carrying three instruments and their associated electronics and a base module with the spacecraft operational subsystems (see Figure 4–4). The instruments included a Diffuse Infrared Background Experiment (DIRBE) to search for cosmic infrared background radiation, a Differential Microwave Radiometer (DMR) to sensitively map cosmic radiation, and a Far Infrared Absolute Spectrophotometer (FIRAS) to compare the spectrum of the cosmic microwave background radiation with a precise blackbody. The three instruments were all located inside a deployable shield in the top half of the spacecraft. The shield protected them from the heat and light of the Sun and Earth, from terrestrial radiation, and from the spacecraft telemetry antenna at the bottom of the spacecraft.[54] A superfluid helium dewar (cryostat), also mounted on the instrument module core structure and similar to that used on the Infrared Astronomical Satellite, housed and cooled the FIRAS and DIRBE instruments to 1.5 K (-271.7°C). COBE carried the first cryogenic scientific instruments with moving parts to fly in a satellite.

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[51] "STEDI: Student Explorer Demonstration Initiative," Mission and Spacecraft Library, Jet Propulsion Laboratory, *http://msl.jpl.nasa.gov/Programs/stedi.html* (accessed September 30, 2005).

[52] "CATSAT, University of New Hampshire," Space Operations Programs, *http://www.sop.usra.edu/catsat.html* (accessed September 30, 2005).

[53] "COBE, Cosmic Background Explorer," *http://library01.gsfc.nasa.gov/gdprojs/projinfo/cobe.pdf* (accessed August 4, 2005).

[54] J.C. Mather et al, "Early Results from the Cosmic Background Explorer (COBE)," COSPAR Conference Proceedings (NASA History Office Folder 5893).

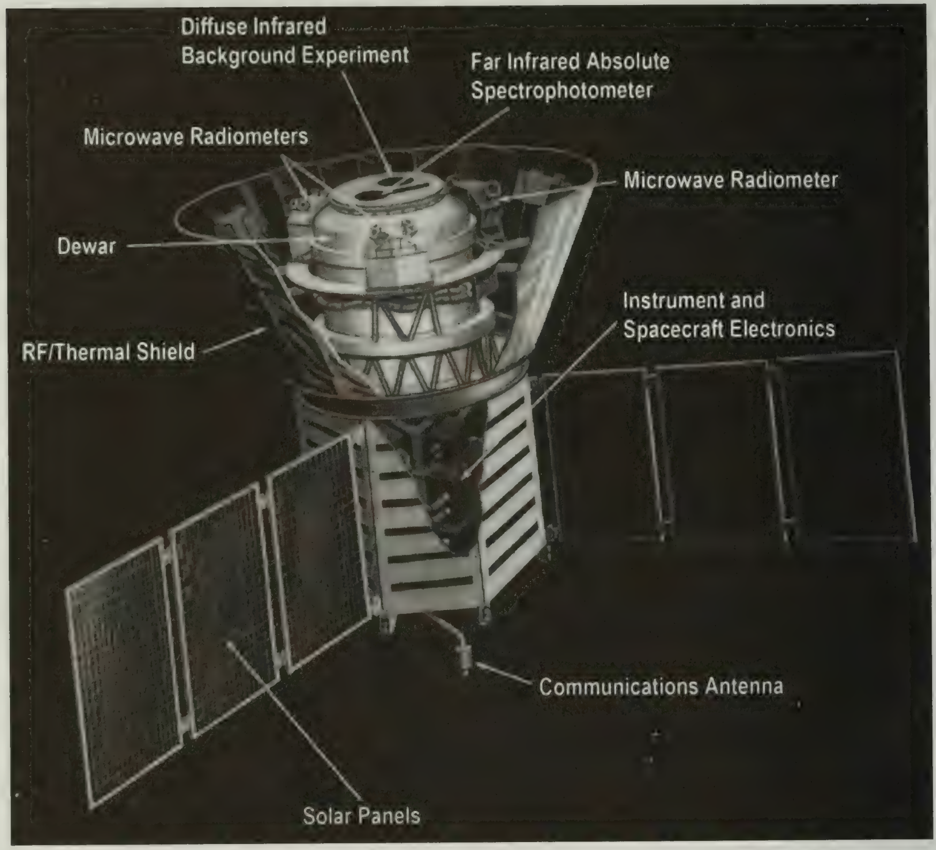
Diffuse Infrared Background Experiment
Far Infrared Absolute Spectrophotometer
Microwave Radiometers
Microwave Radiometer
Dewar
Instrument and Spacecraft Electronics
RF/Thermal Shield
Communications Antenna
Solar Panels

Figure 4–4. COBE Configuration. (CMB Astrophysics Research Program, University of California, Berkeley)

The base module contained the power, communications, and attitude control systems. The orientation of the spin axis was maintained anti-Earth and at 94 degrees to the Sun-Earth line. The operational orbit was dawn-dusk Sun-synchronous so that the Sun remained to the side and the instruments were shielded from it. With this orbit and orientation, the instruments performed a complete scan of the celestial sphere every six months.

COBE was originally planned for a Space Shuttle launch, but the *Challenger* accident, which occurred just before COBE-Shuttle integration was to begin, made this launch impossible. After much study, NASA decided on a West Coast launch into polar orbit using a Delta ELV even though it meant decreasing the weight and volume of the spacecraft by 50 percent to fit within the Delta size and weight constraints.[55]

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[55] A polar orbit was necessary for a survey of the celestial sphere. Dennis McCarthy, "The Cosmic Background Explorer Mission," *1992 Goddard Space Flight Center Research and Technology*, p. 6.

COBE's primary science mission requirement called for one year of observations. In September 1990, the liquid helium supply needed to cool the FIRAS and DIRBE to a temperature below 2 K (-271°C) because full sensitivity became exhausted. During the following months, the temperature inside of the dewar that held the cryogen increased, preventing the FIRAS from operating. DIRBE could still function in the near infrared bands. (The DMR did not require cryogenic cooling and continued remapping the sky to further increase the sensitivity of its measurements.) COBE ended all operations on December 23, 1993, when the DMR was turned off. Beginning in January 1994,[56] Wallops Flight Facility was to use the spacecraft as an engineering training and test satellite.

COBE addressed basic questions of modern cosmology such as how the universe began, how it evolved to its present state, and what forces governed this evolution. According to the Big Bang theory, the universe was created about 15 billion years ago in a violent cosmic explosion that hurled matter in all directions. COBE became well known for its very precise measurements (confirming the Big Bang) and detection of the largest and oldest objects discovered to date. Figure 4–5 shows maps of the full sky in COBE's infrared view of the universe. See Table 4–37 for further mission details.

Extreme Ultraviolet Explorer

The EUVE was the first dedicated EUV mission, conducting the first EUV survey of the sky. The mission carried out extensive spectroscopy observations at EUV wavelengths to help investigators understand the least studied portion of the electromagnetic spectrum.

The EUVE conducted an all-sky, photometric six-month survey (0.1-degree resolution) and a concurrent high-sensitivity photometric survey covering a 2-degree by 180-degree strip along the ecliptic. It carried out spectroscopic observations of bright EUV point sources from 70 angstroms to 760 angstroms. The EUVE also conducted pointed spectroscopy observations of targets identified by guest observers; identified the emission physics of EUV sources such as hot white dwarfs and late-type coronal stars; studied the interstellar medium; and probed whether compelling science could be performed with increased sensitivity in the EUV region.

The spacecraft consisted of four grazing incidence, EUV-sensitive telescopes. Three of the telescopes were co-aligned scanning telescopes mounted perpendicular to the spin axis, and one was a deep survey and spectroscopy telescope oriented along the spin axis. The science payload was attached to a multimission modular spacecraft. The University of California, Berkeley had primary responsibility for the EUVE science payload. See Figure 4–6 for a drawing of the spacecraft.

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[56] "NASA Ends COBE Operations," *NASA News* Release 93-228, December 23, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-228.txt* (accessed August 4, 2005).

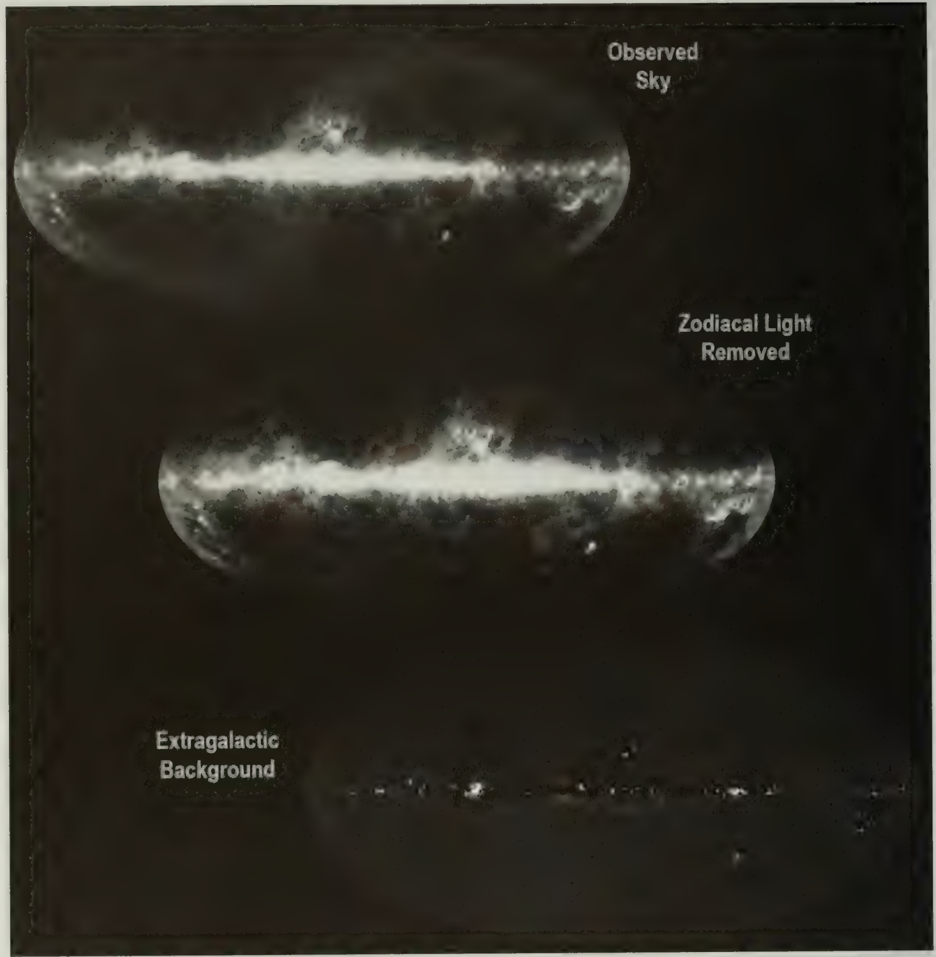

Figure 4–5. COBE's infrared view of the universe. These three pictures are maps of the full sky as seen in infrared light. They were compiled from data taken between December 1989 and September 1990 by COBE's diffuse infrared background experiment. (STScI-PRC 1998-01. Michael Hauser, STScI, the COBE/DIRBE Science Team, and NASA)

The EUVE was launched by a Delta rocket from Cape Canaveral on June 6, 1992, after several launch delays. The spinning spacecraft rotated about the Earth-Sun line. During its early years, the EUVE was operated from Goddard Space Flight Center. A guest observer program, initiated on January 22, 1993, and lasting more than 36 months, followed the initial survey. In 1997, control of the EUVE moved from Goddard Space Flight Center to the University of California, Berkeley, where it remained until the program's end in 2001. Planned to operate for only three years, the EUVE operated for eight years. NASA extended the EUVE's scientific mission twice, but cost and scientific merit issues led NASA to decide to end the mission.[57]

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[57] "EUVE," NSSDC Master Catalog, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1992-031A* (accessed April 20, 2006).

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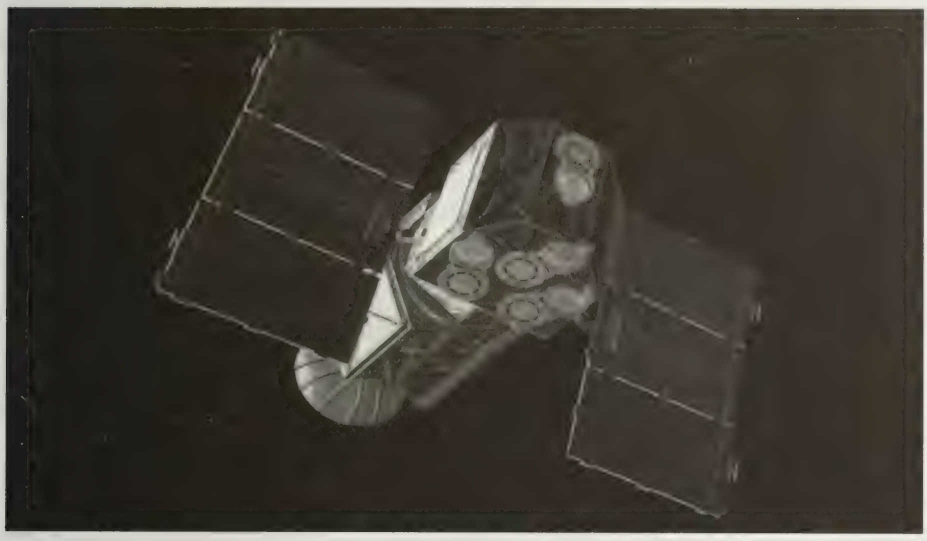

Figure 4–6. EUVE Spacecraft.

In the summer of 2000, NASA decided to end the EUVE mission operations within a few months. The EUVE science operations ended on January 26, 2001, followed by several days of end-of-life mission engineering tests of the never-used backup high-voltage supplies and checking of the remaining battery capacity. The EUVE was stabilized pointing away from the Sun and sent into safehold at 23:59 Universal Time on January 31, 2001. The transmitters were commanded off on February 2, 2001.

The EUVE did not have an on-board propulsion system to allow engineers to control its reentry into Earth's atmosphere. Consequently, although the exact place of reentry into Earth's atmosphere was expected to be somewhere along the spacecraft's orbit track, the precise location was not known until approximately 12 hours before impact. After the transmitters were commanded off in February 2001, the spacecraft was left in a 424-kilometer by 433-kilometer (263-mile by 269-mile) by 28.4-degree orbit. This slowly decayed, and the spacecraft started to break up when it fell to within 80 kilometers (50 miles) of Earth. The EUVE finally reentered Earth's atmosphere over central Egypt on January 30, 2002, and it burned up in the atmosphere.[58] See Table 4–38 for further details.

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[58] "EUVE Spacecraft Re-enters Earth's Atmosphere," *NASA News* Release 02-019, January 31, 2002, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/2002/02-019.txt* (accessed April 20, 2006). The spacecraft entered the atmosphere at 11:15 p.m. Eastern Standard Time on January 30 or 0415 Universal Time on January 31.

Solar Anomalous and Magnetospheric Particle Explorer

The SAMPEX, launched on a Scout rocket in 1992, was the first mission in the SMEX program. NASA engineers at Goddard Space Flight Center designed and built the spacecraft in three years following selection of the mission. The mission studied solar energetic particles, anomalous cosmic rays, galactic cosmic rays, and magnetospheric electrons, and it successfully investigated the composition of local interstellar and solar material and the transport of magnetospheric charged particles into Earth's atmosphere. Dr. Glenn M. Mason of the University of Maryland, College Park, and 10 co-investigators from U.S. and German institutions proposed the SAMPEX study.

The SAMPEX carried four scientific instruments from the University of Maryland, California Institute of Technology, the Aerospace Corporation, and the Max-Planck-Institut für extraterrestrische Physik (Max Planck Institute for Extraterrestrial Physics (MPE)) in Germany. The four instruments, which occupied most of the upper half of the spacecraft, were a complementary set of high-resolution, high-sensitivity, particle detectors studying solar, anomalous, galactic, and magnetospheric energetic particles (see Figure 4–7). The instrument hardware was integrated throughout the primary structure, which consisted of three sensor assemblies, an 8-bit instrument interface microprocessor, and a tank of isobutane for use by one of the sensors.

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The SAMPEX was a momentum-biased, Sun-pointed spacecraft that maintained the experiment-view axis in a zenith direction as much as possible, especially while crossing the polar regions of Earth. The SAMPEX pointed its solar array at the Sun by aiming the momentum vector toward the Sun and rotating the spacecraft one revolution per orbit about the Sun/spacecraft axis.[59] See Table 4–39 for further details.

The SAMPEX was the first mission to use the Small Explorer Data System, developed entirely through the SMEX project at Goddard Space Flight Center. The system used advanced computer technology and solid-state memory (in place of a tape recorder) to store engineering and scientific data and operate the spacecraft autonomously. It provided primary command and control of experiments and spacecraft subsystems, interfaces with the spacecraft communications system, and, with the attitude control system, controlled the spacecraft attitude.[60] The system used a fiber optic data bus to connect the subsystems. Two hemispherical coverage quadrifilar helix antennae were used for ground communication. The average science data rate for the mission was 3 kbps. The spacecraft was configured to operate with two ground contacts per day, each typically lasting 10 minutes. Stored data was transferred to ground stations at a downlink data rate of 900 kbps. Commands were uplinked at 2 kbps.[61]

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[59] "SAMPEX," *http://sunland.gsfc.nasa.gov/smex/sampex/* (accessed July 18, 2006).

[60] "Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) Mission Operation Report," Report no. S-864-92-01, NASA Office of Space Science and Applications, p. 15 (NASA History Office Folder 5895).

[61] "SAMPEX," *http://sunland.gsfc.nasa.gov/smex/sampex/index.html* (accessed August 11, 2005).

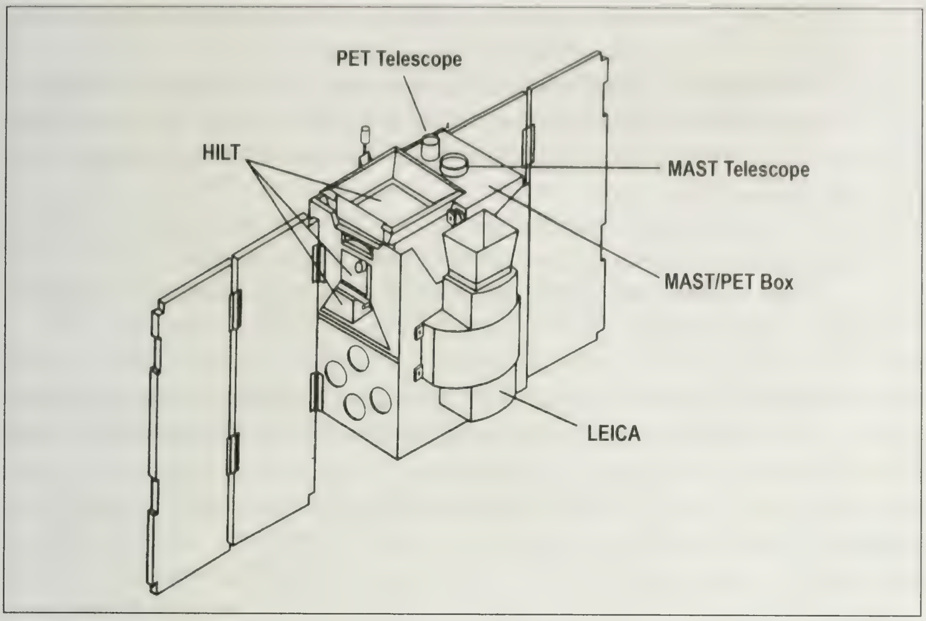

Figure 4–7. SAMPEX Spacecraft.

Rossi X-ray Timing Explorer

The RXTE was designed and built at NASA's Goddard Space Flight Center. Originally called the X-ray Timing Explorer, it was renamed the Bruno B. Rossi X-ray Timing Explorer in February 1996 after astronomer Bruno Rossi, a pioneer in both x-ray astronomy and space plasma physics who discovered the first non-solar source of x-rays. He died in 1993.[62]

The RXTE had three unprecedented capabilities for an x-ray satellite:

1. It measured x-ray flux changes in less than one ten-thousandth of a second. Therefore, the RXTE could track the evolution of material moving at relativistic speeds near neutron stars and black holes.
2. The RXTE detectors had the largest collecting area yet flown and spanned the energy range from 2 keV to 200 keV.
3. The spacecraft and instrument designs allowed the RXTE to change observing plans quickly, so it could usually observe the desired target.

The RXTE spacecraft contained a number of innovations when compared to the Explorer platform that was originally going to serve the XTE mission. These innovations included the following:

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[62] "Who Is Bruno Rossi," The Rossi X-ray Timing Explorer Learning Center, *http://heasarc.nasa.gov/docs/xte/learning_center/name.html* (accessed May 11, 2006).

- A 1-gigabit solid-state memory instead of tape recorders for storing telemetry. This memory allowed a variable telemetry rate.
- A communication system that included two high gain antennae, allowing an almost continuous telemetry stream using the TDRS' Multiple Access mode.
- Consultative Committee for Space Data Systems (CCSDS) packet-based communications.
- Two modern charge coupled device (CCD) star trackers that allowed simultaneous tracking of up to five stars per a star tracker.
- A high-powered Spacecraft Data System requiring the Flight Operations Team to do far less work.[63]

The RXTE carried three instruments: the Proportional Counter Array (PCA), the High Energy Timing Experiment (HEXTE), and the All Sky Monitor (ASM). The power and uniqueness of the RXTE came largely from the synergism of these three instruments and the spacecraft. The spacecraft permitted rapid pointing to almost any point on the sky. The instruments addressed a single objective: the timing and broadband spectra of x-ray sources from 2 keV to 200 keV. The PCA and HEXTE measured short-term variability to microsecond levels. The PCA covered the lower part of the energy range, while the HEXTE covered the upper energy range. The ASM scanned about 80 percent of the sky with every orbit, allowing the ASM to monitor light sources at time scales of 90 minutes or longer. Long-term variability of faint sources could be monitored with repeated brief PCA and HEXTE observations. Data from the PCA and ASM were processed on board by the Experiment Data System.[64] Figure 4–8 shows the spacecraft.

Goddard Space Flight Center operated the RXTE for the astrophysics community. Scientific planning and data processing took place at the RXTE Science Operations Center (SOC). The SOC consisted of the Science Operations Facility, which ran the satellite observatory, and the Guest Observer Facility, which provided scientific services to astronomers using the RXTE. Astronomers at more than 70 universities and laboratories have made observations with the satellite.

The RXTE transmitted data alternately to one of the two NASA TDRSs flying in geosynchronous orbit. A TDRS was in the RXTE's view for 80 percent of its orbit around Earth. The TDRS rebroadcast data to White Sands, New Mexico, which then sent the data to Goddard Space Flight Center. See Table 4–40 for the RXTE mission characteristics.

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[63] "X-Ray Timing Experiment Spacecraft," *http://heasarc.gsfc.nasa.gov/docs/xte/XTEsc.html* (accessed October 20, 2005).

[64] "Taking the Pulse of the Universe," RXTE Brochure, *http://xte.mit.edu/xte_pulse.html* (accessed October 20, 2005). Also "Rossi X-Ray Timing Explorer (RXTE): December 1995–," *http://heasarc.gsfc.nasa.gov/docs/xte/XTE.html* (accessed May 6, 2006).

Fast Auroral Snapshot Explorer

The FAST was the second SMEX mission. It complemented ISTP program investigations. While traversing through the auroral regions, the FAST took high data rate snapshots with electric and magnetic fields sensors and plasma particle instruments to investigate the plasma physics of the auroral phenomena occurring around both poles of Earth. The science investigation made extremely temporal and spatial resolution measurements of the auroral plasma at apogee altitude. The FAST launched in 1996.

The spacecraft orbited in a near-polar, highly elliptical orbit. Apsoidal rotation caused by this orbit configuration positioned the apogee over the North Pole approximately four months after launch. The FAST measurements addressed a broad range of scientific objectives in areas including:

- Electron and ion acceleration by parallel E-fields
- Wave heating of ions-ion conics
- Electrostatic double layers
- Field-aligned currents
- Kilometric radiation
- General wave/particle interactions[65]

The FAST observatory, provided by NASA's Goddard Space Flight Center, was a spin-stabilized spacecraft rotating at 12 revolutions per minute with its spin axis oriented parallel to the orbit axis. The spin rate and spin-axis orientation were maintained by two magnetic torquer coils, one spinning Sun sensor, one horizon crossing indicator, and a spacecraft magnetometer. The attitude control system provided closed-loop spin-rate control.

The body-mounted solar array contained 5.6 square meters (60.3 square feet) of solar cells that could distribute 52 watts of orbit average power to the spacecraft and instruments. The spacecraft hardware consumed an average of 33 watts of power on orbit. The instruments consumed an average of 19 watts of power on orbit, 39 watts when operating. The instruments were frequently powered off to maintain a positive energy balance. See Figure 4–9 for a diagram of the spacecraft.

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[65] "NASA Small Explorer Program–FAST Mission," *http://sunland.gsfc.nasa.gov/smex/fast/mission/* (accessed September 22, 2005).

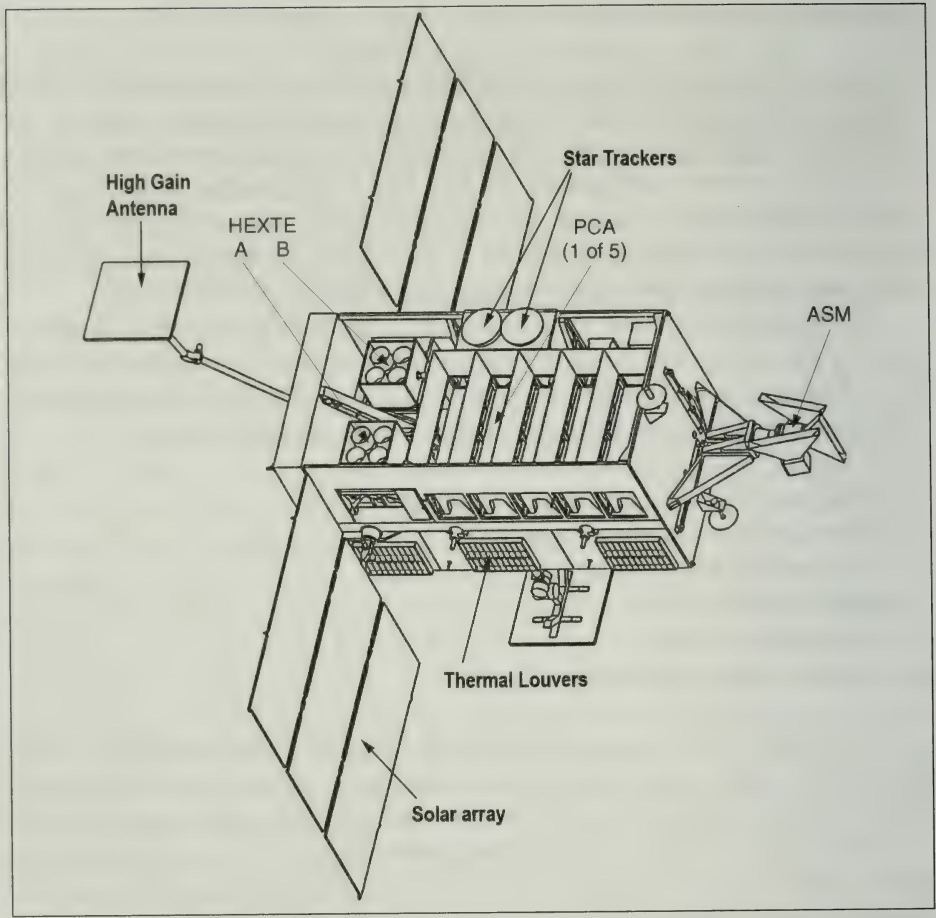

Figure 4–8. Rossi X-Ray Timing Explorer.

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The FAST instrument hardware consisted of the sensor assemblies and an instrument data processor. There were 16 electrostatic analyzers, four electric-field Langmuir probes suspended on 30-meter wire booms, two electric-field Langmuir probes on 3-meter (9.8-feet) extendible booms, searchcoil and flux-gate magnetometers, and a time-of-flight mass spectrometer. The instrument electronics included a 32-bit data processing unit performing science data processing and recording in a one gigabit, solid-state memory. The stored data was transferred to the ground at one of three selectable high data rates of 900 kbps, 1.5 Mbps, or 2.25 Mbps. An average volume of 4 gigabytes to 5 gigabytes per day could be transmitted to Earth during a campaign. While participating in campaigns, the FAST telemetered high-resolution data to the ground on every orbit. Health and safety data was telemetered to the ground at 4 kbps. From the ground stations, the data was moved to Goddard Space Flight Center and then on to the Mission and Science Operations Center at Berkeley, California. The FAST produced nearly 1 terabyte of data in its first two years. During a campaign, the FAST observations were coordinated with those from ground-based equipment, other spacecraft, or aircraft.

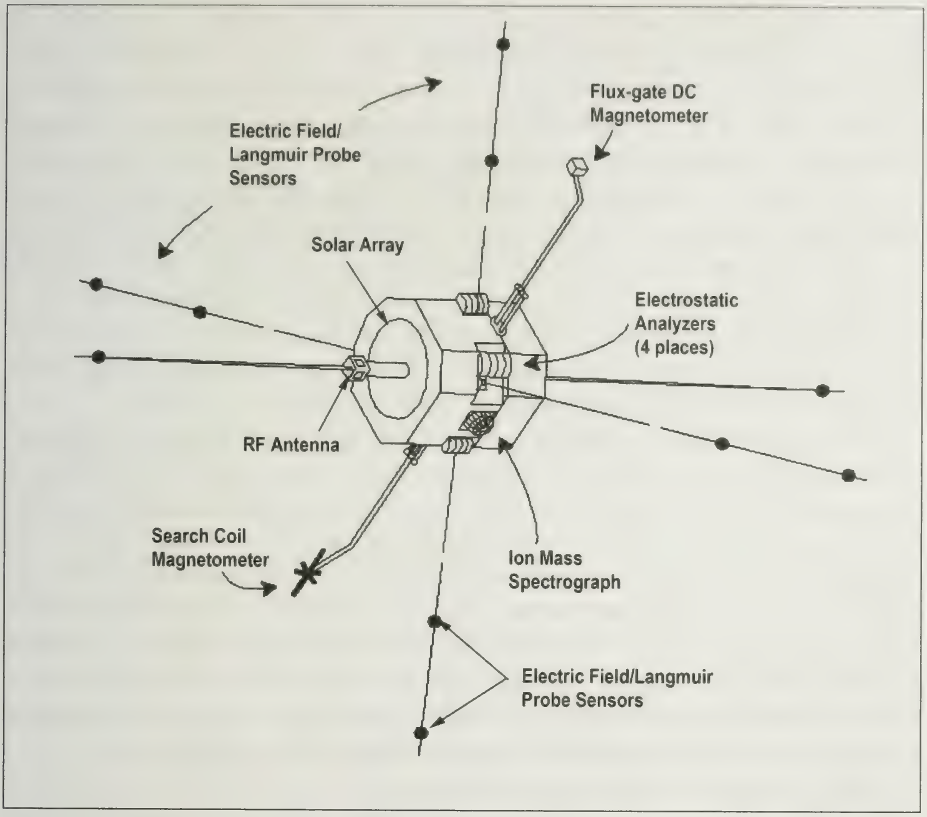
Flux-gate DC Magnetometer
Electric Field/ Langmuir Probe Sensors
Solar Array
Electrostatic Analyzers (4 places)
RF Antenna
Search Coil Magnetometer
Ion Mass Spectrograph
Electric Field/Langmuir Probe Sensors

Figure 4–9. FAST Small Explorer Satellite was made up of particle detectors and magnetic and electric field sensors.

The FAST data system consisted of dual 8085 8-bit spacecraft computers. The spacecraft computers performed health and safety functions, power distribution, data encoding/decoding, and launch vehicle interface. An antenna mounted on a boom above the spacecraft supported ground communications. Commands were uplinked at 2 kbps. A transportable orbital tracking station (TOTS) in Alaska collected real-time science telemetry while the spacecraft was passing through the northern aurora. The TOTS was highly automated and portable; it had an 8-meter antenna with 200 watts of uplink power and could be packed for shipment in three containers.[66] See Table 4–41 for mission details.

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[66] "FAST," *http://sunland.gsfc.nasa.gov/smex/fast* (accessed August 11, 2005).

Advanced Composition Explorer

The ACE spacecraft studied the composition of particles in the solar wind, the local interstellar medium, and galactic matter to better understand the formation and evolution of the solar system. ACE's observations spanned a wide range of energy and intensities, including low-energy particles of solar origin and high-energy galactic particles, with 10 to 1,000 times greater collecting power than past missions. The ACE measured all solar elements from carbon to zinc and determined the masses of individual atomic nuclei over a wide range of velocities.

The ACE was launched in August 1997 during solar minimum conditions, and it observed the transition to solar maximum. During this period, the number of solar flares and coronal mass ejections increased. To escape the effects of Earth's magnetic field, the ACE traveled almost 1 million miles (1.5 million kilometers) from Earth to the Earth-Sun libration point (L1).[67] By orbiting the L1 point, the ACE stayed in a relatively constant position with respect to Earth while Earth revolved around the Sun. Figure 4–10 shows the ACE orbit.

The spacecraft spun about its axis at about five revolutions per minute so that one end always pointed toward the Sun and the other toward Earth.[68] Most of the instruments were located on the top (sunward) deck (see Figure 4–11). The ACE transmitted data to Earth with a highly directional parabolic dish antenna mounted on the aft deck of the spacecraft. Four other broadbeam antennae, capable of transmitting data at lower rates, were also available if needed. Twenty-four hours worth of science and housekeeping data (about 1 gigabit) recorded on one of two solid-state recorders were transmitted to Earth in one 3 to 4-hour telemetry pass each day. A star tracker and digital Sun sensors provided spacecraft attitude. The solar arrays generated about 500 watts of power.

Eight scientific instruments measuring a variety of particle types were mounted on the spacecraft. Booms attached to two of the solar panels carried the ninth instrument—a pair of magnetometers. The ACE instruments covered an unprecedented range of particle types and energy; simultaneous measurements from the instruments were coordinated to create a comprehensive picture of the energetic particles pervading the inner solar system. The nine scientific instruments on the ACE performed comprehensive and coordinated composition determinations and observations spanning a broad dynamic range. They could also provide approximately 1 hour's notice of an impending geomagnetic storm from the Sun. See Table 4–42 for further details.

The ACE was conceived in a meeting on June 19, 1983, at the University of Maryland. This meeting was preceded by preliminary documentation from The Johns Hopkins University Applied Physics Laboratory and the University of Maryland under the proposal name of Cosmic Composition

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[67] "Advanced Composition Explorer (ACE) Mission and Spacecraft Characteristics," *http://www.srl.caltech.edu/ACE/ace_mission.html* (accessed August 11, 2005).

[68] "Advanced Composition Explorer," *http://helios.gsfc.nasa.gov/ACEbrochure-2nd-ed_final.pdf* (accessed August 11, 2005).

Explorer. An unsolicited proposal was assembled and forwarded to the NASA Explorers Program Office later in the year but was not acted upon. The proposal was resurrected and officially resubmitted to NASA in 1986 as part of the Explorer Concept Study Program. In 1988, the ACE mission was selected for a one-year "Phase A" (Concept) Study. This study was a collaborative effort between spacecraft design and science teams.

The ACE mission officially began on April 22, 1991, when the contract between Goddard Space Flight Center and the California Institute of Technology was signed. The Applied Physics Laboratory, designer and builder of the ACE spacecraft, was involved in planning for the definition phase that officially began in August 1992. The early ACE spacecraft effort (April to July 1991) was primarily for ACE mission support, spacecraft system specification, and ACE instrument support and interface definition.

The Mission Preliminary Design Review was held in November 1993. The design and development phase began soon after.[69] The ACE was launched on a Delta II rocket on August 25, 1997. As of 2002, the ACE had sufficient hydrazine to remain in an L1 orbit until 2019, depending on details of the orbit.[70]

Student Nitric Oxide Explorer

The SNOE was the first satellite launched in NASA's STEDI program. STEDI, managed for NASA by the Universities Space Research Association (USRA), was a pilot program to demonstrate that high-quality space science was possible with small, less costly ($4.4 million), free-flying satellites within two years from go-ahead to launch.[71] The spacecraft and its instruments were designed and built at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado. The spacecraft was one of the first NASA satellites entirely operated and controlled by a university. The SMEX, which gathered data on ozone and solar radiation variability from 1981 to 1988, also was controlled at the University of Colorado, Boulder.

Students were involved in all aspects of the SNOE project. Under the supervision of the LASP, they worked on the design study; built the spacecraft and instruments; wrote the flight software; integrated and tested the instruments and subsystems; and integrated the satellite with the launch vehicle. A team of students and mission operations professionals operated the SNOE from the LASP Space Technology Research Building. Advanced undergraduates and graduate students analyzed the data.[72]

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[69] "Advanced Composition Explorer (ACE) Mission Overview," *http://www.srl.caltech.edu/ACE/ace_mission.html* (accessed August 11, 2005).

[70] "Advanced Composition Explorer," 2nd ed., March 2002, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005).

[71] "SNOE," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-012A* (accessed August 31, 2005).

[72] "SNOE Mission Overview," *http://lasp.colorado.edu/snoe/overview.html* (accessed August 31, 2005).

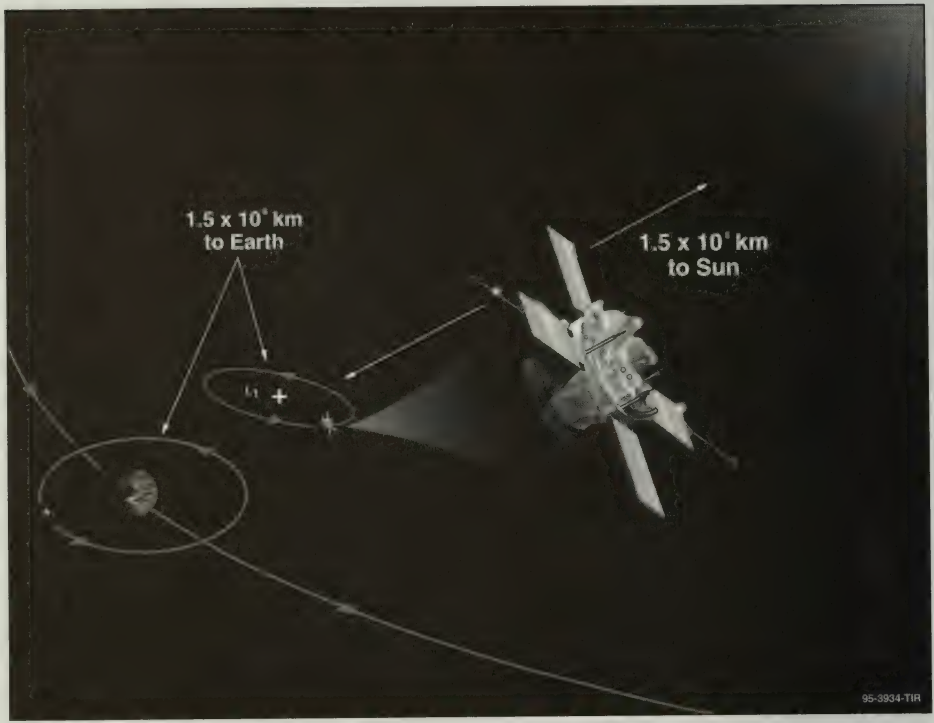

Figure 4–10. ACE L1 Orbit Between Earth and the Sun.

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The SNOE measured the effects of energy from the Sun and the magnetosphere on the density of nitric oxide in Earth's upper atmosphere. Nitric oxide is produced when solar x-rays are absorbed into the atmosphere; the substance destroys naturally produced ozone when injected into the stratosphere 30 miles to 50 miles (48 kilometers to 80 kilometers) above Earth.[73]

The compact, hexagonal scientific spacecraft was launched on February 26, 1998, into a Sun synchronous circular orbit; it began returning science data on March 10. The SNOE spun at five revolutions per minute with the spin axis normal to the orbit plane. The SNOE carried three instruments: a UV spectrometer to measure nitric oxide altitude profiles, a two-channel auroral photometer to measure auroral emissions beneath the spacecraft, and a five-channel solar soft x-ray photometer. The SNOE also carried a special GPS technology investigation built by the Jet Propulsion Laboratory. The spacecraft consumed an average of 35 watts power on orbit, and its data rate was 6 Mb per day. Figure 4–12 shows a computer-generated diagram of the spacecraft structure. See Table 4–43 for additional details. The SNOE reentered the atmosphere on December 13, 2003, descending over the Pacific Ocean west of Peru.

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[73] "CU's 'Little Satellite That Did' Set for Re-entry in Coming Days," *Colorado*, University of Colorado at Boulder News Release, December 1, 2003, *http://www.colorado.edu/news/releases/2003/454.html* (accessed August 31, 2005).

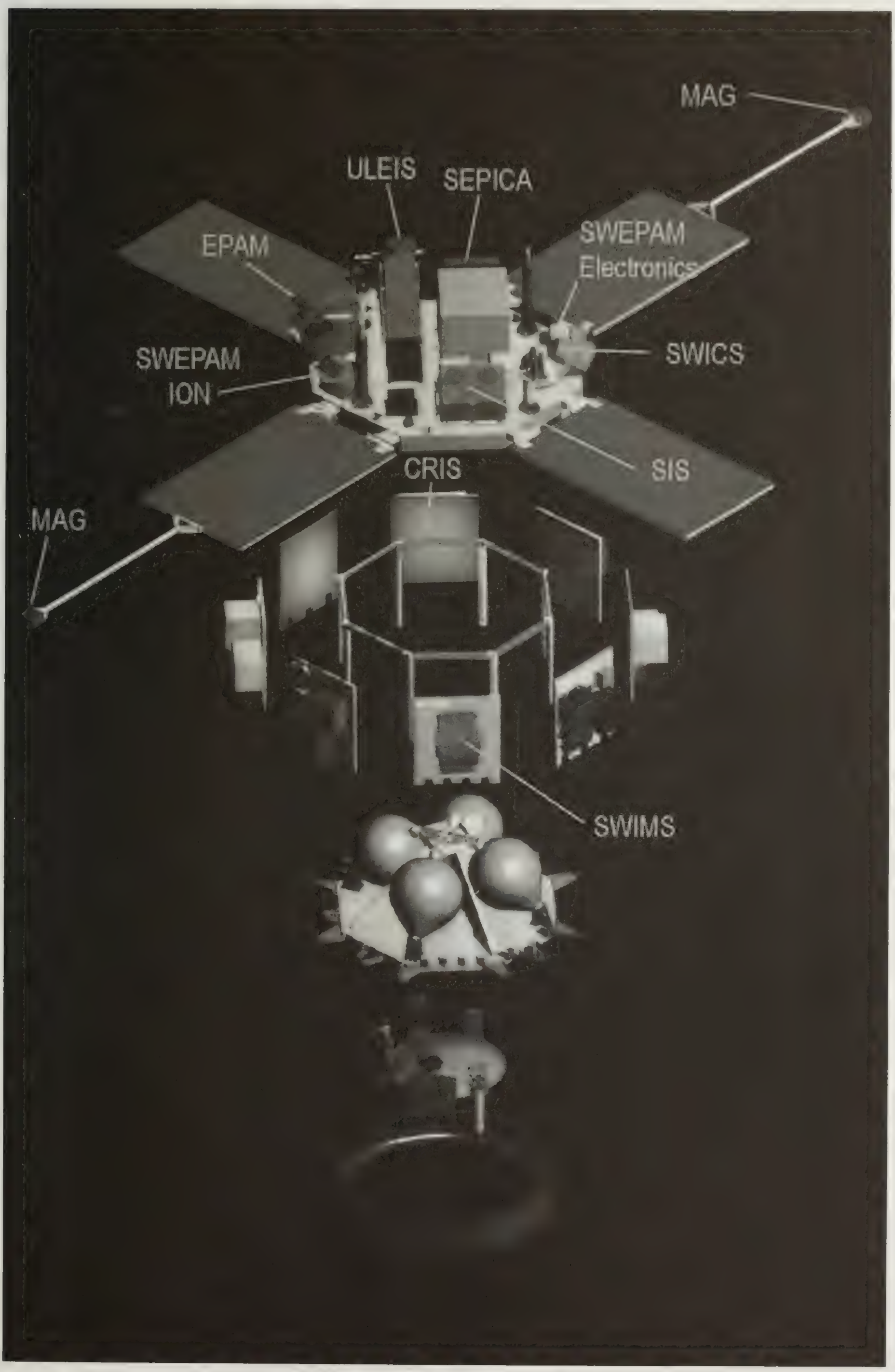
MAG
ULEIS
SEPICA
EPAM
SWEPAM
Electronics
SWICS
SWEPAM
ION
CRIS
SIS
MAG
SWIMS

Figure 4–11. Expanded View of ACE.

Transition Region and Coronal Explorer

The TRACE was a NASA SMEX mission to image the solar corona and transition region at high angular and temporal resolution. It was a key component of NASA's Sun-Earth Connection theme and was the first U.S. solar research mission since the 1980 Solar Maximum Mission.[74] The spacecraft joined a multinational fleet of spacecraft in the ISTP program studying the Sun during a period when solar activity was approaching the peak of its 11-year solar cycle. The mission's science team included scientists from the United States, Sweden, the United Kingdom, and the Netherlands.

The mission was the first U.S. research project with a completely open data policy. All data obtained by the TRACE was available to other scientists, students, and the general public soon after it became available to the primary science team.[75]

The TRACE explored the magnetic field in the solar atmosphere by studying the three-dimensional field structure, the field's temporal evolution in response to photospheric flows, the time-dependent coronal fine structure, and the coronal and transition region thermal topology.[76] The trace observed the Sun to study the connections between fine-scale magnetic fields and the associated plasma structures on the Sun in a quantitative way by observing the photosphere, the transition region, and the corona. With the TRACE, these temperature domains were observed nearly simultaneously (with delays as short as 1 second between different wavelengths), with a spatial resolution of 1 arc second. This was accomplished by obtaining precisely coaligned image sequences of the photosphere, transition region, and corona with high spatial resolution and uninterrupted viewing of the Sun for up to eight months.

The power of the TRACE telescope to perform detailed studies of the solar atmosphere made this observatory unique among the current group of spacecraft studying the Sun. The spacecraft had roughly 10 times the temporal resolution and 5 times the spatial resolution of previously launched solar spacecraft. The telescope's Sun-synchronous orbit was uninterrupted by Earth's shadow for eight months at a time, allowing the telescope the greatest chance to observe the random processes leading to flares and massive eruptions in the Sun's atmosphere. Figure 4–13 shows an image produced by the TRACE.

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[74] "Spacecraft Images Capture Magnetic Energy Burst on Sun," *NASA News* Release 98-92, May 29, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-092.txt* (accessed September 27, 2005).

[75] "Transition Region and Coronal Explorer (TRACE): Exploring the Upper Regions of the Solar Atmosphere," NASA Fact Sheet, FS-1998-01-001-GSFC, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/trace.htm* (accessed September 27, 2005).

[76] "TRACE Science Objectives," *http://trace.lmsal.com/Project/Mission/mission.htm* (accessed September 27, 2005).

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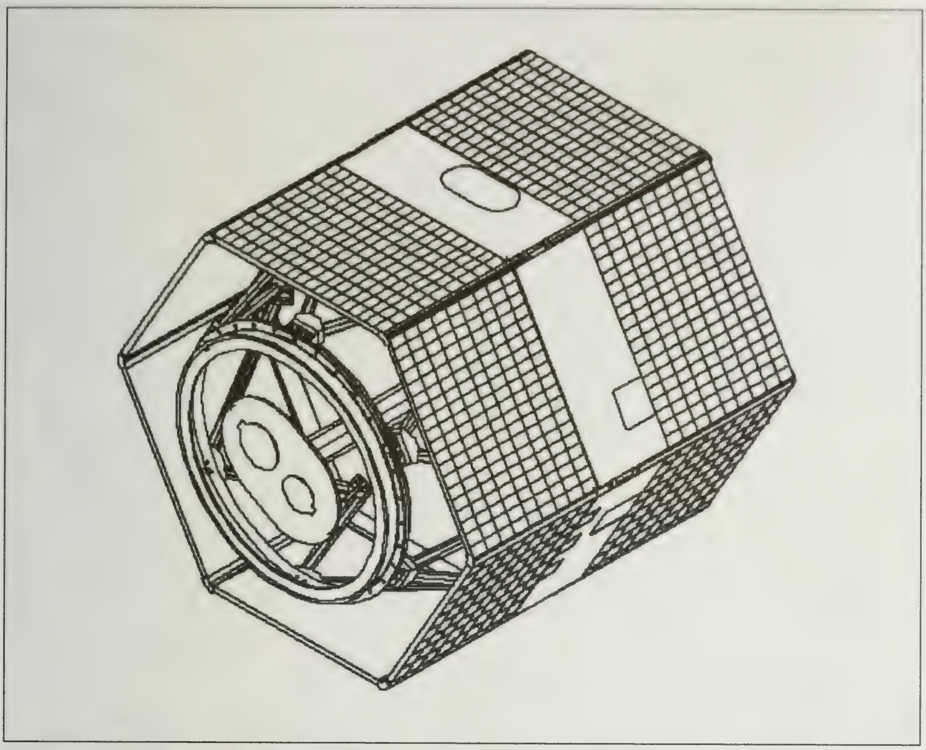

Figure 4–12. SNOE Spacecraft Structure. (Laboratory for Atmospheric and Space Physics)

The TRACE launch was scheduled to allow joint observations with the SOHO during the rising phase of the solar cycle to sunspot maximum. No transition region or coronal imager had ever witnessed the onset and rise of a solar cycle. The two satellites provided complementary observations: TRACE produced high spatial and temporal resolution images, while SOHO yielded images and spectral data out to 30 solar radii at much lower spatial and temporal resolution. Jointly they provided the opportunity to obtain simultaneous digital measurements of all the temperature regimes of the solar atmosphere, in both high-resolution imaging and spectroscopy.[77]

Coordination with the SOHO provided an opportunity to follow the emergence of magnetic flux from the base of the convection zone deep inside the Sun through the photosphere, chromosphere, and transitional region, and then to the low-beta outer corona, while observing the effects of this emergence (such as coronal mass ejections) with high spatial and temporal resolution.[78]

The TRACE was a three-axis stabilized spacecraft with a single telescope. The spacecraft attitude control system used three magnetic-torquer coils; a digital Sun sensor; six coarse Sun sensors; a three-axis magnetometer; four reaction wheels; and three two-axis inertial gyros to maintain pointing. Four panels of Ga-As solar cells provided power to the spacecraft. A 9 amp-hour nickel cadmium battery provided energy when the spacecraft was in Earth's shadow. Communications were provided via a 5-watt S-band transponder, providing up to 2.25 Mbps downlink data transmission and 2 kbps uplink. Data was transmitted up to six times daily. Data was stored on board using a solid-state recorder capable of holding up to 300 MB. The command and data handling system used a 32-bit 80386/80387 processor.[79]

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[77] "TRACE Mission," *http://trace.lmsal.com/Project/Mission/mission.htm* (accessed September 27, 2005).

[78] "TRACE Mission," *http://trace.lmsal.com/Project/Mission/mission.htm* (accessed September 27, 2005).

In science mode, the spacecraft used an instrument-provided guide telescope as a fine guidance sensor to provide pointing accuracy of less than 5 arc seconds. The telescope's mirrors were individually coated in four distinct ways to allow light from different bandwidths to be captured and analyzed. It could detect and examine regions of the Sun ranging in temperatures from 16,000°F to 16,000,000°F (roughly 8,861°C to 8,900,000°C). A CCD detector collected images over a 3,600-mile by 3,600-mile (5,794-kilometer by 5,794-kilometer) FOV, which represented about 25 percent of the Sun's disk or outer edge. A powerful data-handling computer enabled very flexible use of the CCD array, including adaptive target selection, data compression, and image stabilization. Further details are provided in Table 4–44.

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Submillimeter Wave Astronomy Satellite

The overall goal of the SWAS Small Explorer mission was to gain a greater understanding of star formation by determining the composition of interstellar clouds and how those clouds cooled as they collapsed to form stars and planets. The observatory looked at the water and molecular oxygen thought to dominate the chemistry of interstellar clouds. and it looked at carbon monoxide and atomic carbon believed to be major reservoirs of carbon in those clouds. The SWAS measured water, molecular oxygen, atomic carbon, and isotopic carbon monoxide spectral line emissions from galactic interstellar clouds in the 540-micrometer to 616-micrometer wavelength range. Such submillimeter wave radiation could not be detected from the ground because of atmospheric attenuation.

The SWAS measurements provided new information about the physical conditions (density and temperature) and chemistry in star-forming molecular clouds.[80] The SWAS focused on the following spectral lines:

- Water (H_2O) at 556.936 gigahertz
- Molecular oxygen (O_2) at 487.249 gigahertz
- Neutral carbon (CI) at 492.161 gigahertz

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[79] "TRACE," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-020A* (accessed September 27, 2005).

[80] "Submillimeter Wave Telescope," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-071A&ex=** (accessed August 18, 2005).

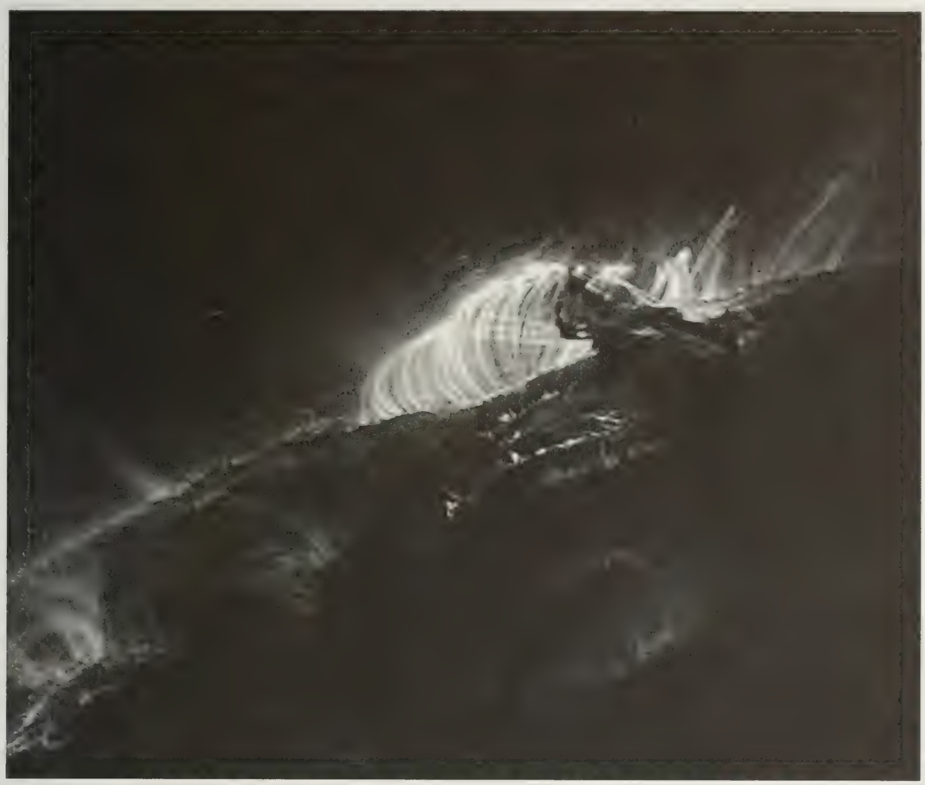

Figure 4–13. TRACE observed this filament eruption on September 30, 1998. It shows a filament very early in its eruption, appearing dark against the backdrop of an arcade of loops; the big, dark filament is rising into interplanetary space with an increasing velocity that already exceeds 100 km/sec. These brightly glowing loops are the result of an earlier flare, cooling down from temperatures of several million degrees. As the loops cool, material drains from them, streaming back toward the solar surface under the influence of gravity. This appears in the image as thin, dark strands of gas at approximately 10,000°C (18,032°F) that absorb EUV emission from other, hotter gases behind them.

- Isotopic carbon monoxide (^{13}CO) at 550.927 gigahertz
- Isotopic water ($H_2{}^{18}O$) at 548.676 gigahertz

The SWAS was a three-axis-stabilized, stellar-pointed observatory with a pointing accuracy of 38 arc seconds and jitter of less than 19 arc seconds. The spacecraft typically pointed its science instrument at three to five targets per orbit. Target selection was constrained so the solar arrays always faced within plus or minus 15 degrees of the Sun except during an eclipse. The SWAS submillimeter wave telescope incorporated dual radiometers and an acousto-optical spectrometer (see Figure 4–14).

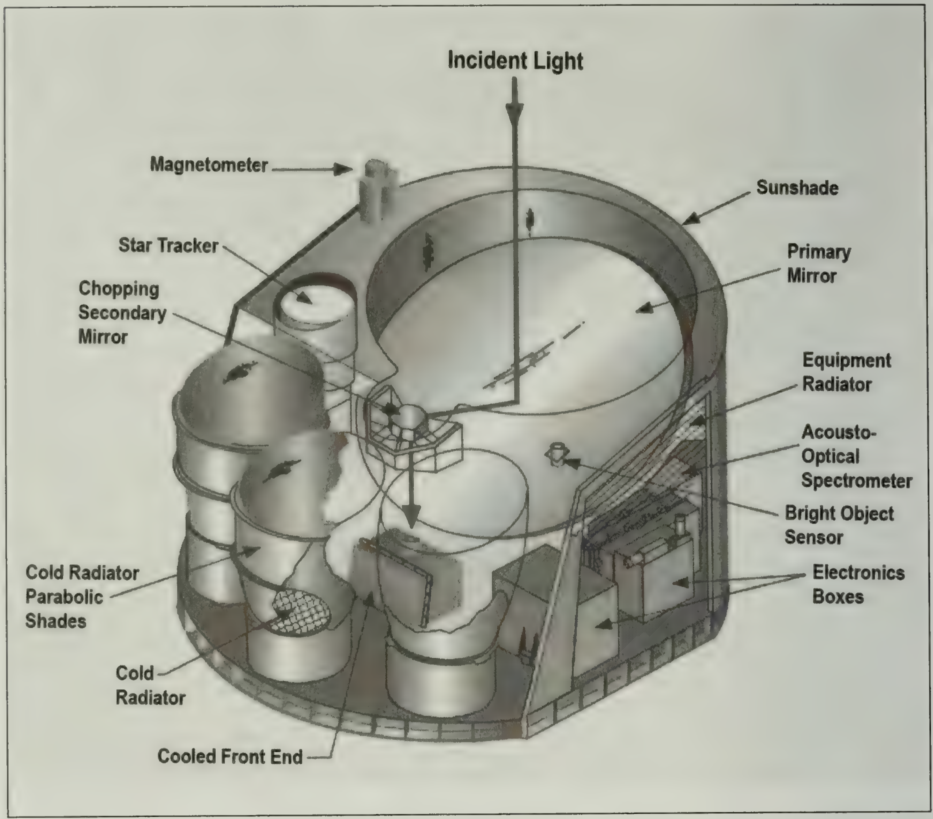
Incident Light
Magnetometer
Sunshade
Star Tracker
Primary Mirror
Chopping Secondary Mirror
Equipment Radiator
Acousto-Optical Spectrometer
Bright Object Sensor
Electronics Boxes
Cold Radiator Parabolic Shades
Cold Radiator
Cooled Front End

Figure 4–14. SWAS Telescope.

Using PI-selected navigation guide stars and an observation timetable generated by the PI, the spacecraft, without ground intervention, "nodded" from an on-source target position to an off-source instrument calibration position up to three degrees away. This nodding occurred approximately every 40 seconds. Attitude control, including pointing and nodding, was accomplished by using three magnetic-torquer coils; one digital Sun sensor; six course Sun sensors; four reaction wheels; one magnetometer; three inertial gyros; and a high accuracy charge coupled device star tracker.

Four deployable, fixed solar panels and one body-mounted panel contained 3.4 square meters (36.6 square feet) of solar cells and provided an average of 230 watts of power on orbit that was distributed to the spacecraft and instrument. The orbit average power consumption of the spacecraft hardware was 150 watts. The instrument consumed 59 watts. See Table 4–45 for further details.

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Far Ultraviolet Spectroscopic Explorer

The FUSE did not launch until June 24, 1999, but the Explorer's development took place during the decade ending in 1998. The FUSE was originally proposed in 1982 to answer a set of fundamental questions about the nature of the universe posed by the Astronomy Survey Committee of the National Academy of Sciences.[81] The mission began as a NASA-managed Explorer project in the mid-1980s. At the time, it was conceived as a midsized mission to explore interplanetary space and study extragalactic light sources. It was to use high-resolution spectroscopy at wavelengths below 1,200 angstroms to measure faint sources both throughout the Milky Way galaxy and at very large extragalactic distances. It would be attached to the Explorer Platform after reaching orbit on the Space Shuttle.

But when the budget ballooned to more than $300 million, NASA looked for a way to restructure the project, and FUSE was extensively redesigned as part of a general restructuring of the Explorers Program. In 1995, The Johns Hopkins University proposed to NASA a way to build the satellite "faster, cheaper, and better" than previously conceived—at a cost of about $100 million and ready to launch two years earlier than originally planned.[82] The Johns Hopkins University proposal was accepted and in November 1995, the FUSE was selected for development leading up to launch on an ELV in October 1998 at a cost of $108 million. The mission was to study the origin and evolution of hydrogen and deuterium, created shortly after the Big Bang, and the forces and processes involved in the evolution of galaxies, stars, and planetary systems.[83]

The FUSE was the first large-scale space mission fully planned and operated by an academic department of a university. The Johns Hopkins University designed and developed it with a global team of corporate and academic partners, including the University of Colorado, the University of California, Berkeley, and the space agencies of Canada and France. The Johns Hopkins University would take control of the scientific mission about 100 minutes after launch and manage it from a mission center in the Center for Physics and Astronomy on the university campus.[84]

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[81] D.J. Sahnow et al, "The Far Ultraviolet Spectroscopic Explorer Mission," poster paper presented at the 1995 American Astronomical Society meeting in Pittsburgh, Pennsylvania, *http://fuse.pha.jhu.edu/papers/technical/aas95/aas95.html* (accessed October 21, 2005).

[82] "FUSE Moves Closer to Launch; Scientists Hope Satellite Uncovers Mysteries of Big Bang's Immediate Aftermath," Headlines@Hopkins News Release, The Johns Hopkins University, August 26, 1998, *http://www.jhu.edu/news_info/news/home98/aug98/fuse.html* (accessed September 28, 2005).

[83] "NASA's Restructured FUSE Program Costs Less, Flies Earlier," *NASA News* Release 95-33, March 21, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-33.txt* (accessed September 28, 2005). Also "NASA Selects FUSE Mission for Development," *NASA News* Release 95-206, November 13, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-206.txt* (accessed September 28, 2005).

[84] "FUSE Moves Closer to Launch; Scientists Hope Satellite Uncovers Mysteries of Big Bang's Immediate Aftermath," Headlines@Hopkins News Release, The Johns Hopkins University, August 26, 1998, *http://www.jhu.edu/news_info/news/home98/aug98/fuse.html* (accessed September 28, 2005).

The FUSE was designed for a very specialized and unique task that complemented other NASA missions. It looked at light in the far UV portion of the electromagnetic spectrum (approximately 90 nanometers to 120 nanometers), observing these wavelengths with much greater sensitivity and resolving power than other instruments that studied light in this range.[85] Astronomers were to use FUSE observations to:

- Understand the origin and history of the chemical elements in the Milky Way galaxy and other nearby galaxies, especially the Large and Small Magellanic Clouds.
- Help trace the history of deuterium, a special form of hydrogen, back to its origin in the Big Bang.
- Explore the origin and circulation of hot and cold gas in the Milky Way and the relationship of these gases with the formation of new generations of stars.
- Provide insight into the origin and evolution of our galaxy by studying a wide range of astronomical objects including hot stars; solar-type stars; remnants of supernova explosions; active nuclei of galaxies and quasars; and planets and comets in the solar system.[86]

The FUSE satellite consisted of two primary parts: the spacecraft and the science instrument. The spacecraft contained all the elements needed to power and point the satellite: the attitude control system, the solar panels, communications electronics, and antennae. The observatory was approximately 7.6 meters (25 feet) long with its baffle fully deployed. The spacecraft and the science instrument each had their own computers, which together coordinated the activities of the satellite.[87] S-band transponders of 5-watt output capacity allowed transmission of the scientific data at a rate of 40 kbps. A complete spectrum could be read in about 7 minutes. Spacecraft housekeeping data and compressed data was downlinked at 2 kbps.

The satellite carried four coaligned telescope mirrors; four focal plane assemblies, each of which contained four apertures; four spherical, aberration-corrected, holographically-recorded diffraction gratings; and two microchannel plate detectors with delay line anodes. A visible light fine error sensor maintained subarcsecond pointing of the entire spacecraft. A composite structure maintained the positions of the optical elements to the several-micron level while the temperature was controlled to 1°C (33.8°F).[88]

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[85] "FUSE Mission Overview," *http://fuse.pha.jhu.edu/overview/mission_ov.html* (accessed September 28, 2005).

[86] "FUSE: Will Further 'Explore' the Big Bang," FS-1999 (03)-008-GSFC, NASA Facts On-Line, NASA Goddard Space Flight Center, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/fuse.htm* (accessed September 28, 2005).

[87] "FUSE Mission Overview," *http://fuse.pha.jhu.edu/overview/mission_ov.html* (accessed September 28, 2005).

[88] D.J. Sahnow et al, "The Far Ultraviolet Spectroscopic Explorer Mission," poster paper.

The PI responsible for developing the overall mission was H. Warren Moos from The Johns Hopkins University. The FUSE was a joint project of NASA and The Johns Hopkins University in collaboration with the French Centre National d'Etudes Spatiales (CNES), the Canadian Space Agency, the University of Colorado, and the University of California, Berkeley.

Explorers Support

The ROSAT and the CRRES missions were not Explorer missions, but they received support or were managed by the Explorers Program.

Roentgen Satellite

The ROSAT was an x-ray observatory developed through a cooperative program between NASA, the United Kingdom, and Germany. NASA viewed the observatory as a stepping stone toward the AXAF, which launched in 1999. Designed, built, and operated by Germany, the ROSAT resulted from a 1975 proposal made by the MPE to the Bundesministeriium für Forschung und Technologie (BMFT) (Federal Ministry for Research and Technology). The original version of the project entailed an all-sky x-ray survey to be carried out with a moderate angular resolution imaging telescope. Between 1977 and 1982, German space companies conducted extensive studies of the project. At the same time, the Carl Zeiss Company began to develop a large x-ray mirror system and the MPE began to develop the focal plane instrumentation. In 1979, to comply with ESA regulations, Germany offered collaboration on the ROSAT to ESA member states. The University of Leicester proposed a wide-field EUV camera to be flown with the main x-ray telescope (XRT) to extend the spectral bandpass to lower energies.[89] The XRT covered the ~6-angstrom to 100-angstrom band, and the wide field camera (WFC) covered the ~60-angstrom to 300-angstrom band. (See Figure 4–15 for a drawing of the ROSAT.)

In 1982, NASA and Germany reached an agreement regarding U.S. participation in the ROSAT project. In return for making 50 percent of pointed observing time available to the PIs from the United States, NASA would provide a high-resolution imager (HRI) for the focal plane of the XRT and launch the satellite on the Space Shuttle. In 1983, Germany and Britain's Science and Engineering Research Council agreed that 12 percent of pointing time would be available to British PIs, and Britain would supply the WFC and associated subsystems. Germany agreed to design, fabricate, test, and integrate the spacecraft and provide the XRT and the two position-sensitive proportional counters (PSPCs) at the focal plane of the telescope. Germany would also handle mission control, tracking, and data acquisition after separation from the Shuttle, as well as initial reduction and distribution of data. In 1983, NASA awarded a sole source contract to the Smithsonian Astrophysical Observatory (SAO) to build flight and engineering model high-resolution imagers and provide integration and launch support. In May 1985, NASA transferred this contract to the Explorers Program at Goddard Space Flight Center for administration and implementation.

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[89] Mission Operation Report, "Roentgensatellit (ROSAT)," Report no. E-876-90-03, p. 6 (NASA History Office Folder 30959).

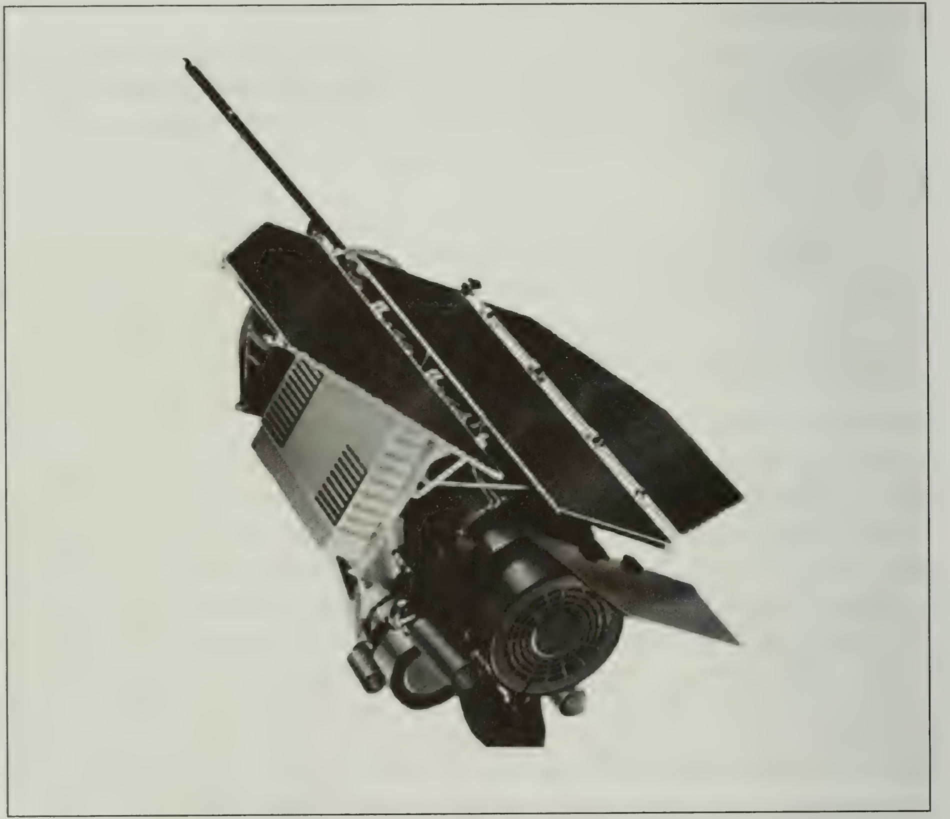

Figure 4–15. ROSAT. (Max-Planck-Institut für Extraterrestrische Physik)

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The *Challenger* accident led to significant changes in the spacecraft design and a launch delay. In December 1987, the decision was made to launch the ROSAT on a Delta II ELV.[90] Germany subsequently modified the spacecraft design and its test and integration procedures to be compatible with the Delta launch vehicle. The United States developed a new 10-foot (3-meter) diameter fairing for the Delta nose section to accommodate the ROSAT's cross-sectional dimension determined by the mounting of the WFC.

The ROSAT was a three-axis stabilized satellite designed for pointing at celestial targets, for slewing between targets, and for performing scanning observations on great circles perpendicular to the plane of the ecliptic. The scientific payload, comprising about two-thirds of the satellite's total weight, was based on two coaligned imaging telescopes. The large XRT was the primary telescope. It measured "soft" x-rays in the energy range from 0.1 keV to 2 keV (corresponding to wavelengths of 100 angstroms to 6 angstroms). The WFC extended the measuring range to the EUV region by covering the energy range from 0.04 keV to 0.2 keV (300 angstroms to 60 angstroms). (See Figure 4–16 for a diagram of the satellite.)

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[90] Max Planck Institut Für Extraterrestrische Physik, *ROSAT User's Handbook, http://agile.gsfc.nasa.gov/docs/rosat/ruh/handbook/handbook.html* (accessed August 9, 2005).

The German Space Operations Center in Oberpfaffenhofen, Germany, operated the satellite using the German Deep Space Station near Weilheim, Germany, for command functions and receipt of data from the on-board tape recorders. NASA tracking station support was limited to launch preparations, early mission operations, and backup in emergencies.

The mission consisted of two phases: a six-month all-sky survey phase conducted by German scientists using the PSPC, and a pointed phase (also called the Guest Observer phase) that began in February 1991. The all-sky survey with imaging x-ray and EUV telescopes resulted in the most sensitive, complete x-ray and map of the sky to date. This survey led to the discovery of about 80,000 x-ray and 500 EUV sources from which observers could choose targets during the Guest Observer phase.

During the guest observer program, which spanned 7.5 years and involved some 650 PIs from 26 countries, about 9,000 fields in the sky were observed. Numerous discoveries were made, and more than 4,000 scientists published more than 3,000 scientific articles and reports. The program ended in November 1998 after the HRI, an x-ray camera built by the SAO under contract to NASA, accidentally scanned too close to the Sun on September 20, causing irreversible damage to its collecting plate. This was an unavoidable event after ROSAT engineers in April lost control of the satellite's navigational system, which had deteriorated after eight years in space. Scientists made two final days of observations starting on December 7 by using reserved gas and the PSPC. The PSPC naturally exhausted its xenon gas supply in 1994 and has been inactive ever since. The two-day reserve gas allowed the PSPC to turn on and make one last observation of a few important astrophysical objects such as Supernova 1987A, which had been the ROSAT's very first target in 1990.

The ROSAT's discoveries spanned subjects as diverse as the relatively nearby Moon and comets to the most distant high redshift quasars, from tiny neutron stars to clusters of galaxies, the largest physical objects in the universe.[91] The ROSAT was the first observatory to detect x-rays from the Moon. In the distant universe, the spacecraft resolved virtually all of the cosmic x-ray background into discrete quasars and galaxies. See Table 4–46 for further mission details.

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[91] "End of the ROSAT Guest Observer Programme," ROSAT Status Report #175: ROSAT News no. 67 (November 3, 1998) *http://heasarc.gsfc.nasa.gov/mail_archive/rosnews/msg00118.html* (accessed August 8, 2005).

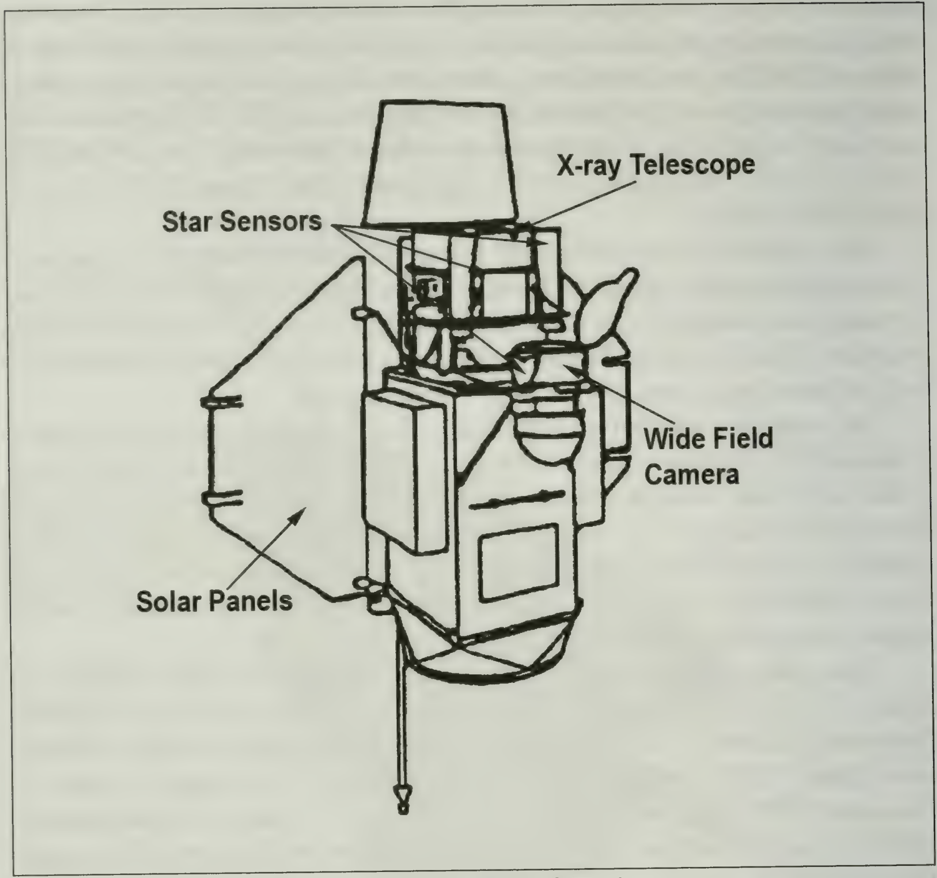

Figure 4–16. ROSAT Configuration.

Combined Release and Radiation Effects Satellite

The CRRES was a joint project of NASA and the U.S. Air Force. The Explorer Program managed the NASA portion of the mission. The CRRES was launched on July 25, 1990, into a highly elliptical geosynchronous transfer orbit (GTO) to conduct complex scientific research in "Earthspace," the space environment just above Earth's atmosphere that included the ionosphere and magnetosphere with its invisible magnetic and electrical fields and particles.[92] The CRRES carried five payloads of experiments on high-efficiency solar cells, ionospheric structure and chemistry, and radiation effects on microelectronic devices. The satellite also contained a NASA chemical payload comprising 24 chemical canisters ejected from the main spacecraft and releasing chemicals at specific times during the mission.

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[92] "Combined Release and Radiation Effects Satellite (CRRES) Press Kit," General Release, p. 2, *http://www.lightwatcher.com/chemtrails/CRRES_%20Presskit.html* (accessed August 5, 2005).

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The CRRES program began in 1983 as a joint NASA-U.S. Air Force project resulting from two separate programs, NASA's Chemical Release Module (CREM) program and the Air Force's Space Radiation program. Originally, the dual-mission spacecraft was to carry 48 canisters of chemicals to release after the spacecraft had been deployed from the Space Shuttle in low-Earth-orbit (LEO) at 215 miles (346 kilometers) altitude. At LEO, the spacecraft would have performed chemical release experiments for 90 days. Following the LEO mission, a trans-stage motor would have placed the CRRES into GTO, where additional chemical releases and the primary DOD mission would take place.

The loss of *Challenger* in January 1986 forced a major restructuring of the CRRES program. In June 1987, NASA decided to launch the CRRES directly to GTO on an Atlas-Centaur ELV carrying 24 canisters, complemented by a program of sounding rocket launches to perform some of the experiments excluded from the original 48-canister CRRES mission. Modifications also included the removal of a large orbit transfer stage, replacement of the orbiter cradle with a payload adapter to mate with the Centaur upper stage, and relocation of the solar panels to fit into the Atlas I fairing.

The 24 chemical canisters were ejected from the satellite during the first 13 months of the mission. The 16 large and 8 small canisters released clouds of metal vapor about 100 kilometers (62 miles) in diameter that interacted with the ionospheric and magnetospheric plasma and Earth's magnetic field. The vapors were released approximately 25 minutes after the canisters were ejected to avoid contaminating the spacecraft. The canisters performed 14 experiments. Seven experiments took place at altitudes ranging from 1,200 miles to 21,000 miles (1,931 kilometers to 33,800 kilometers); the remaining seven were undertaken near perigee at altitudes between 240 miles and 300 miles (386 kilometers and 483 kilometers). In June 1991, contact was lost with the CRRES, and the mission ended before the sounding rocket experiments could take place.

NASA's experiments were in four areas:

- Magnetospheric Ion Cloud Injections: This group of experiments artificially seeded the magnetosphere with plasma and, working with DOD particle and electromagnetic wave investigators, used ground-based optical and radar diagnostics to observe large-scale changes in the cloud. *In situ* CRRES measurements examined smaller local phenomena. The CRRES instruments also determined the state of the magnetosphere, providing valuable data to allow determination of optimal conditions for releases (experiments G-1 through G-7, G-10).
- Ionospheric Modifications: This group of experiments introduced disturbances into the ionosphere to study friction forces from the interaction of high-speed injected plasmas and the ionosphere. Scientists also injected neutral atoms at orbital velocities to understand why

unusually efficient ionization occurred when a fast beam of neutral gas passed through magnetized plasma. Scientists compared the observed behavior of the injected plasmas with computer models (experiments G-8, G-9, G-13, G-14).

- Electric Fields and Ion Transport: This group of experiments studied the low-latitude electric fields and the movement of ions along magnetic field lines into the ionosphere in response to these electric fields (experiments G-11, G-12).
- Ionospheric Irregularity Simulators: These experiments were to produce large-scale releases of chemicals to study irregularities in the ionosphere and the effects of the ionosphere on the propagation of high-frequency waves. This was the sounding rocket portion of the mission, and this portion did not take place because contact was lost with the spacecraft in October 1991, before these experiments were scheduled to begin (experiments AA-1 through AA-7).

Further details can be found in Table 4–47.

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The Great Observatories

The Great Observatories were a series of four space-borne observatories designed to conduct astronomical studies over many different wavelengths (visible, gamma rays, x-rays, and infrared). Each Great Observatory focused on a different part of the spectrum. Their overlapping operations phases enabled astronomers to make contemporaneous observations of an object at different spectral wavelengths. During the 1989–1998 decade, NASA launched two of four Great Observatories, launched the third in 1999, and also largely developed the fourth.

Hubble Space Telescope

The Hubble Space Telescope was the first Great Observatory. The Hubble Space Telescope was deployed by Space Shuttle *Discovery* on April 25, 1990. Subsequent Shuttle missions serviced the Hubble Space Telescope, recovering the full capability of its imperfect mirror and adding additional capabilities. The telescope observes the universe at UV, visible, and near-infrared wavelengths.

The Hubble Space Telescope is a large Earth-orbiting astronomical telescope that observes the heavens above and without the interference and turbulence of Earth's atmosphere. The idea for a "large orbital telescope" originated in 1946 when Lyman Spitzer, a world-renowned theoretical astrophysicist, wrote "Astronomical Advantages of an Extra-terrestrial Observatory," discussing the advantages of an orbiting observatory over a ground-based telescope.[93] After the success of NASA's Orbiting Astronomical Observatories in the late 1960s and early 1970s, NASA developed plans for a Large Orbiting Telescope to launch in 1970. Regular "manned maintenance missions" were part of the plan for the telescope to ensure a long and useful life. During the 1970s, astronomers and other proponents of the telescope lobbied Congress for project funding. In 1977, Congress approved funding for the Large Space Telescope, soon to be named the Hubble Space Telescope after Edwin Hubble.[94]

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[93] Lyman S. Spitzer, Jr., "History of the Space Telescope," *Quarterly Journal of the Royal Astronomical Society* (March 20, 1979): pp. 29–36.

The original plan for the Large Space Telescope program called for the telescope's return to Earth, refurbishment, and relaunch every five years, with on-orbit servicing every two and one-half years. Hardware lifetimes and reliability requirements were based on such an interval between servicing missions. In 1985, contamination and structural loading concerns associated with return to Earth aboard the Shuttle eliminated the idea of the telescope's ground return. NASA decided that on-orbit servicing might be adequate to maintain the Hubble Space Telescope's 15-year design life and adopted a three-year cycle of on-orbit servicing.[95]

The Hubble Space Telescope was scheduled for a 1986 launch, but the destruction of *Challenger* in 1986 delayed launch until 1990. Between 1986 and launch in 1990, engineers intensively tested and evaluated the spacecraft, assuring the greatest possible reliability. An exhaustive series of end-to-end tests involving the Space Telescope Science Institute (STScI), Goddard Space Flight Center, the TDRS System, and the spacecraft were performed, resulting in overall improvements in system reliability.

In October 1989, the telescope was shipped by a U.S. Air Force C5A aircraft from the Lockheed Martin plant in Sunnyvale, California, to the launch site at Kennedy Space Center. The spacecraft was installed in *Discovery*'s payload bay on March 29, 1990.

The Hubble Space Telescope was launched on April 24, 1990, and it began approximately six months of orbital-systems checkout and calibration. On May 20, at 11:12 a.m. Eastern Daylight Time, the telescope transmitted its first image, or "first light," a 1-second exposure of open-star cluster NGC 3532 from the telescope's WFPC. A second, 30-second exposure was taken at 11:14 a.m. The image in Figure 4–17 compares the first Hubble Space Telescope image to an image from a ground-based telescope of the same portion of the sky.

Despite great NASA and astronomer celebration, it was clear that there were problems with the images. Astronomers noticed "hairy tendrils" and "spiderlike tentacles emanating like spokes from the center of each of the bright stars" in the images. Additional WFPC images acquired about 10 days later had similar features. The first images taken with the European-built Faint Object Camera (FOC) on June 17 also seemed "strangely unfocused" and showed the "same kind of irksome halo . . . with the same spidery tendrils and other odd radial structure surrounding each star's pointlike cusp of light." The unclear image was indicative of "spherical aberration, an optical flaw that invariably blurs part of a star's light energy over a larger area than expected, . . . a condition that could be caused only by a mirror of the wrong shape."[96]

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[94] Spitzer, "History of the Space Telescope" : p. 34.

[95] "Overview of the Hubble Space Telescope," Space Telescope Science Institute, *http://www.stsci.edu/hst/HST_overview/* (accessed September 5, 2005).

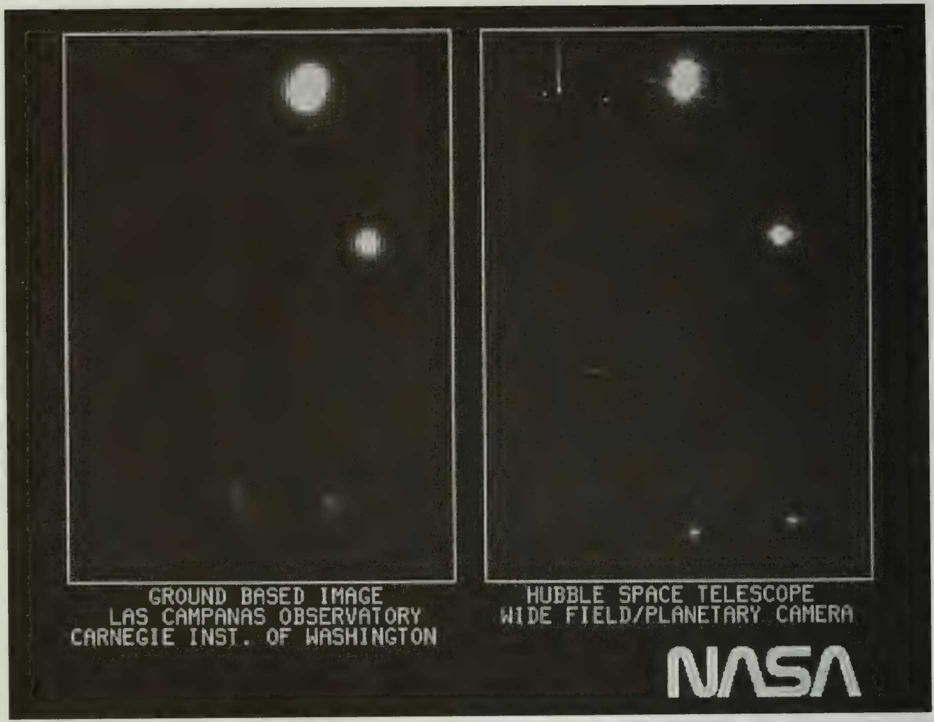

Figure 4–17. Hubble Space Telescope's "First Light," May 20, 1990. On the right is part of the first image taken with Hubble Space Telescope's Wide Field/Planetary Camera. The left shows a ground-based picture from the Las Campanas, Chile, Observatory of the same region of the sky taken with a 100-inch telescope. It is typical of high-quality pictures obtained from the ground. The images of the stars in the ground-based picture are fuzzy and, in some cases, overlap because of smearing by Earth's atmosphere. The same stars in the Hubble Space Telescope frame are sharper and well resolved, as shown by the double star at the top of the image. (STScI-PRC90-04)

Elation quickly turned to dismay, and on June 21 the Hubble Space Telescope's project manager announced the telescope's inability to focus properly. On June 25, spherical aberration was discovered in the telescope's primary mirror.[97] On July 2, NASA Associate Administrator for Space Science and Applications, Dr. Lennard A. Fisk, appointed a Hubble Space Telescope Optical Systems Board of Investigation, headed by Dr. Lew Allen, director of JPL, to review, analyze, and evaluate the facts and circumstances regarding the manufacture, development, and testing of the Hubble Space

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[96] Eric J. Chaisson, *The Hubble Wars* (New York: Harper Collins Publishers, 1994), pp. 137–138, 143, 166.

[97] "Historical Timeline," *http://hubble.nasa.gov/overview/timeline.php* (accessed September 20, 2005).

Telescope Optical Telescope Assembly.[98] During the next five months, the board met and determined that the problem resulted from a flawed measuring device at the Perkin-Elmer plant where the telescope's mirrors had been made. A mirror defect 1/50 the width of a human hair prevented the telescope from focusing all light at a single point.[99]

Although many believed the spherical aberration, which was not detected during manufacturing, would cripple the telescope, scientists quickly found a way to use computer enhancement to work around the abnormality. Targets were revised to give priority to UV astronomy in front of visible light astronomy.[100] Even with the flaw, the Hubble Space Telescope saw objects at 5 billion to 10 billion light-years away with as much detail as objects at 1 billion light years seen with telescopes on Earth.[101]

A second major defect also was discovered. Problems with the solar panels caused degradation in the spacecraft's pointing stability. When passing in and out of the orbital shadow, thermal expansion and contraction from heating and cooling of the arrays caused the panels to undergo a transient distortion. This induced a jitter strong enough for the telescope's pointing and control system to lose lock on the target stars.[102] A final serious telescope problem, premature failure of the gyroscopes, also needed to be remedied.[103]

Because of these serious problems, NASA changed the primary objective of the 1993 first servicing mission from replacing the WFPC with an improved camera and performing routine maintenance to correcting the Hubble Space Telescope's primary mirror spherical aberration, replacing the faulty solar arrays, and installing new gyroscopes to replace faulty ones.[104] The repair mission aboard STS-61 in December 1993 successfully replaced the gyroscopes and solar panels and installed corrective lenses, greatly improving image quality and restoring much of NASA's credibility. Details of the servicing mission can be found later in this section. Figure 4–18 shows the M100 galaxy before and after the first servicing mission.

The Hubble Space Telescope weighs approximately 24,500 pounds (11,110 kilograms) and is 43.5 feet (13.3 meters) long and 14 feet (4.3 meters) in diameter at its widest point, roughly the size of a railroad tank car or bus. Many of the telescope's components are modular so they may be removed and replaced on orbit by astronauts. It is the first spacecraft specifically designed for on-orbit servicing.

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[98] "Hubble Board of Investigation Named," *NASA News* Release 90-091, July 2, 1990, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1990/90-091.txt* (accessed September 20, 2005).

[99] "Did You Know," *Goddard News* Special Edition (1993): 4. (NASA History Office Folder 005989).

[100] Randee Exler, "HST Promises 'Excellent Science,'" *Goddard News* 36 (July 1990): 1, 8.

[101] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," Office of Space Science, Report no. X 458-61-93-02, November 1993, p. 2 (NASA History Office Folder 005989).

[102] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," pp. 1–2.

[103] Gyroscopes sense changes in orientation so the spacecraft can be "pointed" in the desired direction. Chaisson, pp. 58–59.

[104] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission." Report no. X 458-61-93-02, pp. 1–2.

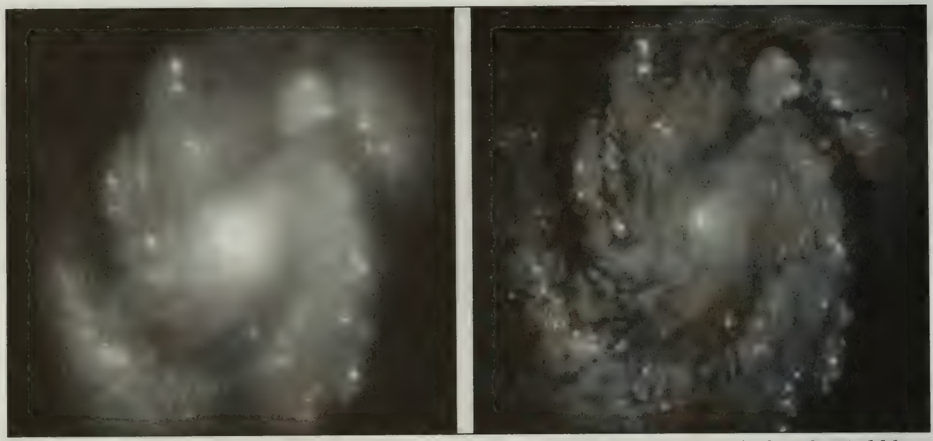

Figure 4–18. These images of Spiral Galaxy M100 were taken before and after the Hubble Space Telescope's first servicing mission. The image on the left was obtained with the original Wide Field/Planetary Camera. The image on the right was obtained with the Wide Field and Planetary Camera 2 that was installed on the servicing mission. Both the new device and the COSTAR were designed to compensate for the primary mirror's incorrect shape. (NASA and STScI-PRC1995-49e)

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The Hubble Space Telescope has three major elements: the support systems module, the optical telescope assembly, and the scientific instruments. The support systems module consists of the exterior structure and the various systems that enable the optical telescope assembly and scientific instruments to operate. Foil-like multilayer insulation wraps the telescope. To keep it from overheating, the metallic silver surface reflects much of the direct sunlight striking the telescope. Tiny heaters attached to many telescope components warm them during the "eclipse" phase of orbit, when in Earth's shadow. The insulation blankets and solar-powered heaters maintain the mirror temperature at 70°F (21°C). Solar arrays, built by the ESA, convert the Sun's energy to electricity during the portion of orbit when the telescope is exposed to sunlight. These two "wings" contain 48,000 solar cells. Power is stored in six nickel-hydrogen batteries to support the telescope during eclipse.

A series of gyroscopes, star trackers, reaction wheels, fine guidance sensors, and electromagnets form the pointing control system. When conducting an observation, the pointing control system rotates the space telescope to the proper orientation, points it to the desired star, and locks the telescope in place. The gyroscopes and reaction wheels produce a course pointing toward the star. Star trackers (or fine guidance sensors) fine-tune the course pointing. These sensors can locate and lock onto a position in the sky to within 0.01 arc second and can hold that pointing without varying more than 0.007 arc second for as long as 24 hours while the Hubble Space Telescope continues to orbit Earth at 17,500 miles per hour (28,163 kilometers per hour).

The three fine guidance sensors on the Hubble Space Telescope are located at 90-degree intervals around the telescope's circumference. They serve a dual purpose. Two fine guidance sensors point the telescope at an astronomical target and then hold the target in a scientific instrument's FOV. The third fine guidance sensor can also be used as a scientific instrument to obtain highly accurate celestial positions (astrometry).

Other systems include a computer that controls the overall spacecraft; high-gain antennae that receive ground commands and transmit data back to Earth; an electrical power system; the spacecraft structure and mechanical parts; and the safing system, which controls the telescope to protect it from damage in case of serious computer problems or loss of communication with ground controllers.

The telescope assembly contains two mirrors that collect and focus light from the celestial objects being studied. The 94-inch (239-centimeter) primary mirror is near the center of the telescope. The precision-ground glass has an aluminum reflecting surface and is the smoothest large mirror ever made. To reduce weight, the front and back plates are fused to a honeycomb core. The 13-inch (33-centimeter) secondary mirror is located 16 feet (4.9 meters) in front of the primary mirror. It is set far enough inside the open end of the telescope to assure that stray light does not interfere with the image being studied. Three baffles surround the path of light to block out unwanted rays. To resist the expansion and contraction of the mirrors resulting from exposure to the temperature extremes of space, the mirrors are made from a kind of glass that resists expansion and contraction. An extremely strong, lightweight structure holds the mirrors at a precise distance from each other. The truss is made from graphite epoxy, a material resistant to expansion and contraction in temperature extremes.[105]

During observations, light from a celestial source travels through the tube of the telescope to the large primary mirror. The light is then reflected from the primary mirror back to the secondary mirror. From there, the beam narrows, then passes through a hole in the center of the primary mirror to a focal plane where the scientific instruments are located almost 5 feet (1.5 meters) behind the primary mirror.[106] (Figure 4–19 shows the light path for the main telescope.)

The Hubble Space Telescope's science instruments work together and individually to view the farthest reaches of space. Originally, the telescope accommodated five science instruments and three fine guidance sensors. Each instrument was contained in a separate module and operated on 110 watts to 150 watts of power. Four instruments were aligned with the main optical axis and were mounted just behind the primary mirror. At deployment, these axial instruments were the Goddard High Resolution Spectrograph (GHRS); the Faint Object Spectrograph (FOS); the FOC; and the High Speed Photometer (HSP). The fifth science instrument, the WFPC, was located in the radial bay.[107] Figure 4–20 shows the overall Hubble Space Telescope configuration.

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[105] "Space Shuttle Mission STS-31 Press Kit," April 1990, pp. 6, 9, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_035_STS-031R_Press_Kit.pdf* (accessed September 5, 2005).

[106] "Space Shuttle Mission STS-31 Press Kit," April 1990, p. 15.

[107] "Hubble's Science Instruments," *http://hubble.nasa.gov/technology/instruments.php* (accessed September 12, 2005).

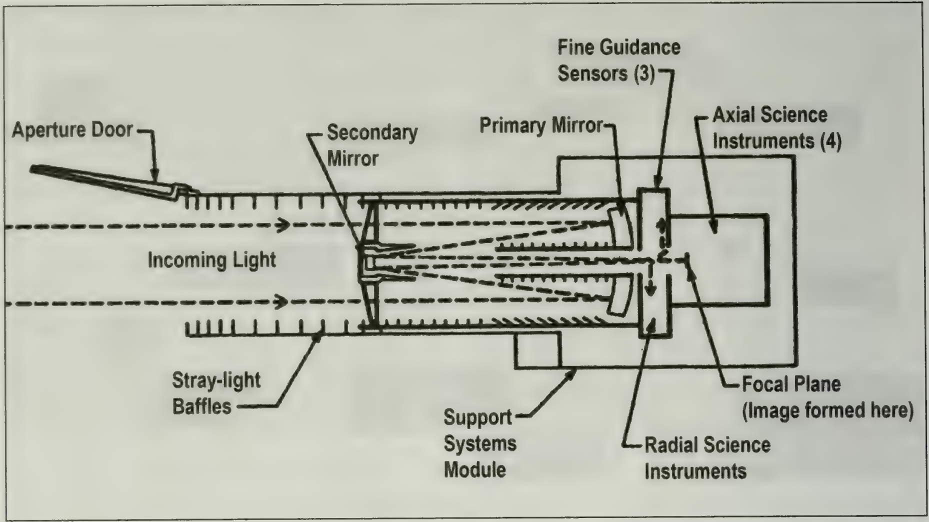
Fine Guidance Sensors (3)
Aperture Door
Secondary Mirror
Primary Mirror
Axial Science Instruments (4)
Incoming Light
Stray-light Baffles
Support Systems Module
Focal Plane (Image formed here)
Radial Science Instruments

Figure 4–19. Light Path for the Main Telescope. (STS-61 Press Kit)

The Hubble Space Telescope was a collaborative effort. Marshall Space Flight Center was responsible for the telescope's design, development, fabrication, and assembly. The Center also conducted orbital verification of the observatory's systems after launch. Project management for the telescope was transferred from Marshall Space Flight Center to Goddard Space Flight Center when the orbital verification phase was almost complete. Goddard Space Flight Center was responsible for developing four of the scientific instruments and the telescope's ground data system, which included management and oversight of the Space Telescope Science Institute at The Johns Hopkins University in Baltimore (later called the STScI). The STScI conducts and coordinates the telescope's science operations. The Association of Universities for Research in Astronomy, Inc. (AURA) operates the STScI for NASA. The ESA played a significant role in telescope development by providing the electrical power-producing solar arrays and the FOC.

Johnson Space Center directs the Space Shuttle mission operations phase of the servicing mission. It supplies the Shuttle and all Shuttle-associated hardware and trains astronaut crews to rendezvous with the Hubble Space Telescope and repair and/or replace instruments and spacecraft hardware. Kennedy Space Center readies the Shuttle for launch, supervises placement of the telescope's payload elements in the Shuttle cargo bay, and provides Shuttle launch services.

Hubble Space Telescope Servicing

The Hubble Space Telescope was the first scientific mission specifically designed for routine on-orbit servicing by spacewalking astronauts. The modular design allowed astronauts to disassemble it, replace worn-out equipment,

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and upgrade instruments. These periodic servicings ensured that the Hubble Space Telescope continued to produce first-class science using the latest and most advanced technology. Each time a Hubble Space Telescope science instrument was replaced, it increased the telescope's scientific power by a factor of 10 or greater.[108]

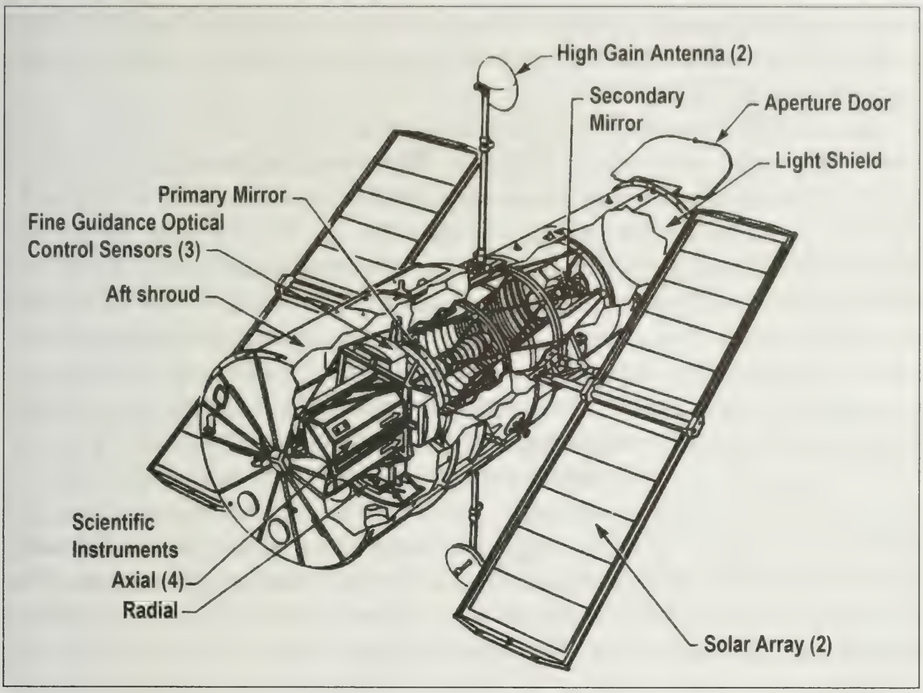
High Gain Antenna (2)
Secondary Mirror
Aperture Door
Light Shield
Primary Mirror
Fine Guidance Optical Control Sensors (3)
Aft shroud
Scientific Instruments
Axial (4)
Radial
Solar Array (2)

Figure 4–20. Hubble Space Telescope Configuration. (STS-31 Press Kit)

Servicing Mission 1 (SM1). Before Hubble Space Telescope's 1990 launch, a planned servicing mission had been scheduled for 1993 to install an updated Wide Field and Planetary Camera 2 (WFPC2) and perform general maintenance. But when problems with the telescope's mirror, solar arrays, and gyroscopes surfaced on orbit, NASA established additional requirements for the first servicing mission. The primary mission objectives became correcting spherical aberration in the telescope's primary mirror and replacing the spacecraft's faulty solar arrays and inoperative gyroscopes.

The COSTAR, built by Ball Electro-Optics and Cryogenics Division for installation on SM1, corrected spherical aberration of the main mirror by better focusing the light sources for the axial instruments. (The WFPC2 had its own corrective optics.) To install the COSTAR, one of Hubble Space Telescope's four axial instruments had to be removed. Because the HSP did proportionately less science than the other instruments, NASA decided that astronauts would replace the 200-kilogram (441-pound), phone-booth-sized HSP by pulling it out through a servicing bay door and installing the COSTAR in its place. The COSTAR had no cameras or detectors. It used 10 precisely shaped corrective mirrors (each about the size of a quarter) placed with mechanical arms in front of openings on each of the three remaining observing instruments, to refocus the light relayed from the flawed primary mirror before it entered the instruments, much like "putting a pair of glasses on the Space Telescope."[109]

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[108] "Hubble Space Telescope: An Introduction," *http://hubble.nasa.gov/overview/intro.php* (accessed September 6, 2005).

The WFPC2 was a spare instrument developed in 1985 by JPL; it was to be installed as a replacement during the first servicing mission. TheWFPC2 had new sensors that improved sensitivity, particularly in the UV portion of the spectrum. When the primary mirror flaw was discovered soon after launch, NASA and the camera team immediately began work on an optical correction that could be built into the upgraded camera. The new design had corrective optics to compensate for the Hubble Space Telescope primary mirror flaw and small actuators to fine tune the position of its internal mirrors to ensure correct alignment. The astronauts would slide out the original 280-kilogram (670-pound) wedge-shaped WFPC and replace it with WFPC2.

The replacement solar arrays were the original flight spare arrays that the ESA modified to eliminate the jitter problem. The modifications included the addition of thermal shields to reduce temperature gradients on the solar blankets' deployment booms and the redesign of boom-length-compensation and blanket-tension mechanisms. When deployed, each solar array measured approximately 12 meters by 3 meters (40 feet by 10 feet).[110]

This mission was nearly the most challenging and complex human spaceflight operation ever attempted. STS-61 lifted off from Kennedy Space Center on December 2, 1993. The *Endeavour* crew captured the Hubble Space Telescope on December 4, grappling and berthing it in the Shuttle's cargo bay. Over the next five days, two teams of astronauts carried out the servicing tasks during a record five back-to-back EVAs totaling 35 hours, 28 minutes.

During the first EVA, Jeffrey Hoffman and F. Story Musgrave replaced two sets of remote sensing units containing the gyroscopes that helped the telescope point in the correct direction. They also replaced eight fuse plugs protecting the telescope's electrical circuits. Thomas Akers and Kathryn Thornton performed the second EVA, in which the astronauts replaced the telescope's two solar arrays. EVA 3, performed by Hoffman and Musgrave, replaced the WFPC with the new WFPC2 and also changed out two magnetometers (see figure 4–21). EVA 4, performed by Akers and Thornton, replaced the HSP with the COSTAR. They also upgraded the Hubble Space Telescope's on-board computer by bolting

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[109] "Corrective Optics Contract for Hubble Telescope Awarded," *NASA News* Release C91-oo, October 16, 1991 (NASA History Office Folder 005989).

[110] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," Report no. X 458-61-93-02, November 1993, p. 10 (NASA History Office Folder 005989).

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on an electronics package containing additional computer memory and a coprocessor. The final EVA, performed by Hoffman and Musgrave, replaced the solar array drive electronics, fitted an electrical connection box on the GHRS, and installed covers on the magnetometers.

The flight control team for Hubble Space Telescope operations on SM1 was divided between Johnson Space Center and Goddard Space Flight Center. The Goddard Space Flight Center Mission Manager, located at Johnson Space Center, coordinated the activities at both Johnson Space Center and Goddard Space Flight Center. The Shuttle flight was controlled from the Johnson Mission Control Center where EVA and payload-trained specialists assisted the normal complement of Shuttle flight controllers. At Goddard Space Flight Center, teams of engineers and scientists provided operational control of the Hubble Space Telescope until it docked with *Endeavour*. They conducted real-time commanding of the telescope to safe systems before EVAs, accomplished aliveness and functional tests on in-flight-serviced hardware, and provided troubleshooting expertise when required.

The Hubble Space Telescope was disconnected and moved from the Shuttle on December 9. Once released from *Endeavour*, Hubble Space Telescope command and control reverted solely to Goddard Space Flight Center, and a three and one-half-month period of observatory verification began. During that time, systems and subsystems were checked out and scientific instruments were aligned to the telescope's optical axis and calibrated to the characteristics of the newly installed corrective optics.

The verification period demonstrated the success of the SM1 repairs and replacements. Change-out or installation of all items on the entire servicing task list was accomplished and scientific capabilities were restored. Post-mission images proved the effectiveness of the optical corrections, and vehicle systems were restored to a fully redundant status. The mission proved the concept of on-orbit servicing as the way to keep the Hubble Space Telescope fully functional and performing cutting-edge astronomy.[111]

Key science enabled by the corrected image quality yielded the following:

- An accurate measurement of the expansion rate of the universe (the Hubble constant).
- The deepest look ever at the properties of galaxies in the early universe (the Hubble Deep Field).
- Initial spectroscopic detections of massive black holes in the centers of galaxies.
- The first detection of helium in the intergalactic medium.
- Unprecedented views of star formation and the late stages of stellar evolution (e.g., Orion protoplanetary disks, SN1989a).[112]

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[111] "Post-Launch Mission Operation Report for the Hubble Space Telescope First Servicing Mission," April 28, 1994 (NASA History Office Folder 30976).

[112] "The Evolving Role of Satellite Servicing at NASA," presented by Frank Cepollina to the Association of Space Explorers, USA, June 22, 2004, Houston, Texas.

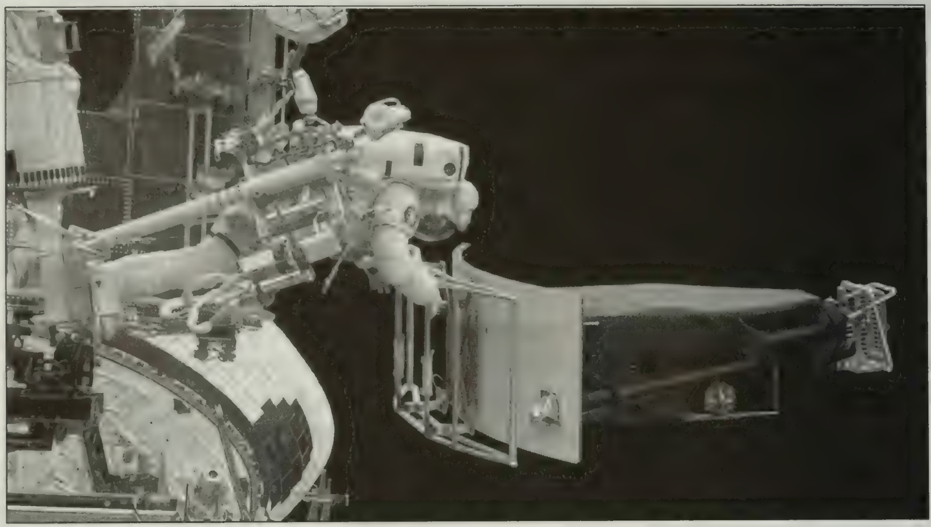

Figure 4–21. Replacing the Wide Field Planetary Camera During the Hubble Space Telescope's First Servicing Mission. (NASA Photo, 1993, http://imgsrc.hubblesite.org/hu/gallery/db/spacecraft/15/formats/15_print.jpg*)*

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Servicing Mission 2 (SM2). On the Hubble Space Telescope's second servicing mission, which launched from Kennedy Space Center on February 11, 1997, the six-member STS-82/*Discovery* crew completed servicing and upgrading of the Hubble Space Telescope during four planned EVAs and then performed a fifth unscheduled spacewalk to repair telescope insulation. Astronauts upgraded the telescope's scientific capabilities by installing two new instruments—the STIS and NICMOS—and performed telescope maintenance. The telescope received a refurbished fine guidance sensor, a solid-state recorder to replace one of the reel-to-reel tape recorders, and a refurbished spare reaction wheel assembly (RWA) to replace one of the on-board assemblies.

The STIS replaced the GHRS. The new instrument included all the major capabilities of the GHRS and FOS, and added new technological capability. The STIS optical design featured internal corrective optics to compensate for the Hubble Space Telescope's primary mirror spherical aberration and did not use the COSTAR. The NICMOS replaced the FOS. Like STIS, the NICMOS design featured corrective optics to compensate for the primary mirror's spherical aberration. The addition of the STIS powerful general-purpose spectroscopic capability and the NICMOS near-infrared capability yielded the following:

- A systematic survey of black hole properties in galaxy nuclei.
- An infrared companion image to the Hubble Deep Field, showing even more distant galaxies.
- Spectroscopic detection of the atmosphere of a planet in another solar system.[113]

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[113] "The Evolving Role of Satellite Servicing at NASA," presented by Frank Cepollina.

The Hubble Space Telescope's original data management system included three reel-to-reel tape recorders to store engineering and science data that could not be transmitted to the ground immediately. Unlike the reel-to-reel recorder, the new solid-state recorder had no reels, tape, or moving parts to wear out. It was about the same size as the reel-to-reel recorder, but it could store 10 times as much data in computer-like memory chips until the telescope's operators at Goddard Space Flight Center commanded the recorder to play it back; the new solid-state recorder stored 12 gigabits of data, while the tape recorder stored only 1.2 gigabits.

The Hubble Space Telescope communicated with the ground through NASA's orbiting TDRS System. Engineering information from the spacecraft systems and science data from the astronomical instruments could either be sent directly to the Space Telescope Operations Control Center at Goddard Space Flight Center or recorded and played back later. The current procedure was to record all science data to ensure continuity and safeguard against any possible loss of unique information. Post-servicing mission plans were to use the solid-state recorder, with larger capacity and flexibility, exclusively for science data storage. This would accommodate the higher data rates from the new science instruments and promote greater operational efficiency.

By the second servicing mission, one of the fine guidance sensors in the Hubble Space Telescope's pointing control system was showing signs of mechanical wear and was due for replacement. The fine guidance sensor had a new mechanism to accomplish better optical alignment. When this spare replaced one of the original units, telescope operators could compensate for changes in on-orbit conditions and optimize its performance by keeping the fine guidance sensor more finely tuned.

Other replacements during SM2 included the following:

- Replacement of one of the telescope's four reaction wheel assemblies with a refurbished spare.
- Replacement of one of the four data interface units with a modified and upgraded spare unit that corrected original unit failures.
- Replacement of the solar array drive electronics unit, not replaced during SM1, with the unit returned from orbit on SM1. The unit was refurbished to correct for problems that resulted in transistor failures. The ESA provided the solar array drive electronics units.
- Installation of more durable covers for magnetic sensing system hardware because of degradation of materials in the space environment.
- Replacement of one of the three engineering and science tape recorders with a spare because one unit failed.
- Installation of an optical control electronics enhancement kit.

Astronaut Steven Hawley, one of the astronauts who originally deployed the telescope, operated *Discovery's* remote manipulator system arm on STS-82 to retrieve the Hubble Space Telescope for its second servicing on February 13, 1997, and positioned it in the payload bay less than half an hour later. Figure 4–22 shows a close-up of the Hubble Space Telescope taken by *Discovery's* still camera.

Relying on more than 150 tools and crew aids, Mark Lee and Steven Smith performed EVAs 1, 3, and 5, and Gregory Harbaugh and Joseph Tanner accomplished EVAs 2 and 4. The spacewalks on STS-82, which took place in more than five days, totaled 33 hours, 11 minutes, about 2 hours less than the total EVA time recorded on the telescope's first servicing mission.

On the first EVA, Lee and Smith removed two scientific instruments from the Hubble Space Telescope, the GHRS and FOS, and replaced them with the STIS and NICMOS, respectively. On EVA 2, Harbaugh and Tanner replaced a degraded fine guidance sensor and a failed engineering and science tape recorder with new units. They also installed an optical control electronics enhancement kit, which increased the capability of the fine guidance sensor. During this EVA, astronauts noted cracking and wear on thermal insulation on the side of the telescope facing the Sun and in the direction of travel.

During EVA 3, Lee and Smith removed and replaced a data interface unit as well as an old reel-to-reel tape recorder with a new digital solid-state recorder that allowed simultaneous recording and playback of data. They also changed out one of the four reaction wheel assembly units that used spin momentum to move the telescope toward a target and maintain it in a stable position. After this EVA, the mission managers decided to add EVA 5 to repair the Hubble Space Telescope's thermal insulation.

On EVA 4, Harbaugh and Tanner replaced a solar array drive electronics package controlling the positioning of the telescope's solar arrays. They also replaced covers over the telescope's magnetometers and placed thermal blankets of multilayer material over two areas of degraded insulation around the light shield portion of the telescope below the top of the observatory. Meanwhile, inside *Discovery*, Horowitz and Lee worked on the middeck to fabricate new insulation blankets for the Hubble Space Telescope.

On EVA 5, the final spacewalk, Lee and Smith attached several thermal insulation blankets to three equipment compartments at the top of the telescope's support systems module, which contained key data processing, electronics, and scientific instrument telemetry packages.

The Hubble Space Telescope redeployed on February 19 and moved into the highest altitude it had ever flown, a 335-nautical-mile by 321-nautical-mile (620-kilometer by 594-kilometer) orbit. Calibration of the two new science instruments took place during a period of several weeks with first images and data returned after about two months.

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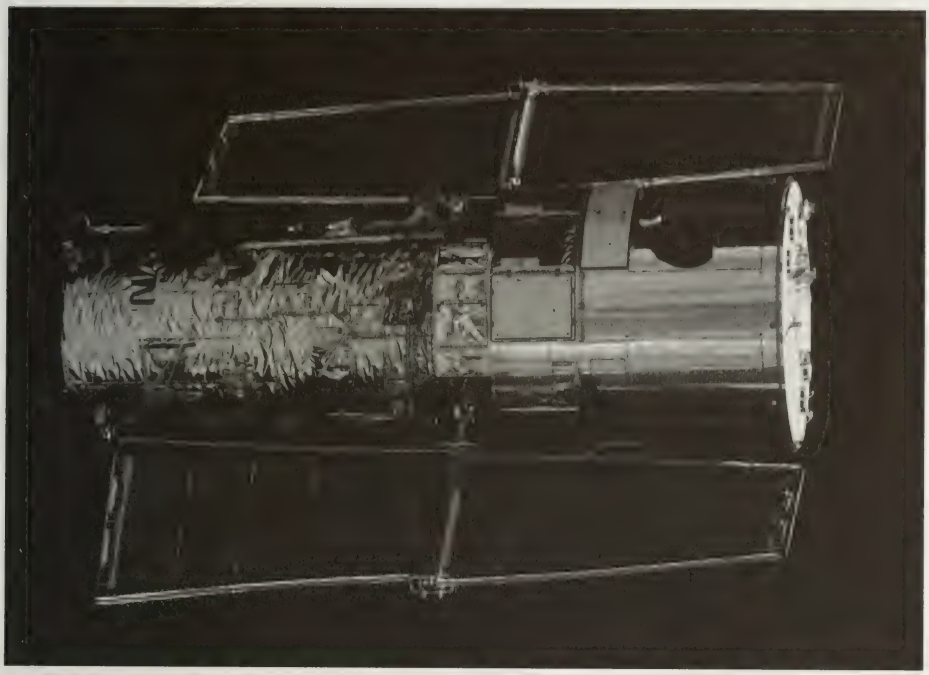

Figure 4–22. The first close-up look at the Hubble Space Telescope since 1993 was provided by the STS-82 electronic still camera during Discovery*'s rendezvous with the giant telescope. (NASA Photo No. STS82-E-5084)*

Hubble Orbiting Systems Test Mission

The HOST mission took place on STS-95 in October 1998. This Space Shuttle mission, dubbed "the John Glenn Mission" because of its famous crew member, tested key pieces of new Hubble hardware before installation on the Hubble Space Telescope. By flying in an orbit similar to the telescope's, the HOST allowed engineers to determine how new equipment on this flight would perform on the telescope.

HOST engineers monitored the effects of radiation on the telescope's new hardware, including an advanced computer, digital data recorder, and cryogenic cooling system. All the new technologies on the HOST mission performed as expected. Table 4–48 provides mission details.

Hubble Space Telescope Science

As stated in the announcement of opportunity released in 1977, the Hubble Space Telescope's main scientific objectives were to investigate the following:

- The constitution, physical characteristics, and dynamics of celestial bodies.
- The nature of processes occurring in the extreme physical conditions existing in and between astronomical objects.

- The history and evolution of the universe.
- Whether the laws of nature are universal in the space-time continuum.

From launch through 1998, the Hubble Space Telescope delivered a steady stream of new clues and discoveries to help solve the mysteries of the cosmos. Making great strides in achieving its scientific goals, the Hubble Space Telescope capitalized on its breadth of vision, which ranged from the UV to the near infrared, to help scientists answer some of the most puzzling questions of our universe while raising some new ones. The Hubble Space Telescope contributed significantly to most of the topics of current astronomical research, covering objects from our own solar system to the most distant galaxies. The following section describes some of the telescope's most significant discoveries. Material was drawn primarily from "The Hubble Space Telescope: Science in the First Decade," at the *HubbleSite* Web site.[114]

Cosmic Collision. The Hubble Space Telescope allowed astronomers an outstanding view of the impact of Comet Shoemaker-Levy 9 on Jupiter. During July 16–22, 1994, 21 fragments of the comet plunged into Jupiter, exploding with the force of millions of nuclear bombs. The telescope's high-resolution images provided acute details of the plumes' geometry, the growth and dispersion of the impact features, and the atmospheric waves expanding around the impact sites, even while the precise nature of these waves continued to generate debate. The comet impact was a relatively rare phenomenon, where a thousand years might pass before a similar event is observed again. Figure 4–23 shows eight impact sites on Jupiter.

Life Cycle of Stars. The Hubble Space Telescope documented in great detail the births and deaths of stars. The telescope visually demonstrated that protoplanetary dust disks around young stars are common, suggesting that at least the raw materials for planet formation are in place. The Hubble Space Telescope showed for the first time that jets in young stellar objects emanate from the centers of accretion disks (in objects such as Herbig Haro 30), thus turning what were previously theoretical expectations into observed reality. The Hubble Space Telescope provided many very detailed images of stellar deaths in the form of morphologies of planetary nebulae, a mysterious three-ring structure around Supernova 1987A, and corrugated bipolar lobes in the Luminous Blue Variable Eta Carinae (see figures 4–24 and 4–25). While some of the basic physics developed for these objects from earlier ground-based observations has not changed significantly, the realization that almost none of these objects are spherically symmetrical, but rather that bipolarity and point-symmetry was extremely common, stimulated much theoretical work on nebular shaping.

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[114] "The Hubble Site," *http://hubblesite.org/discoveries/10th/vault/in-depth/science.shtml* (accessed September 9, 2005).

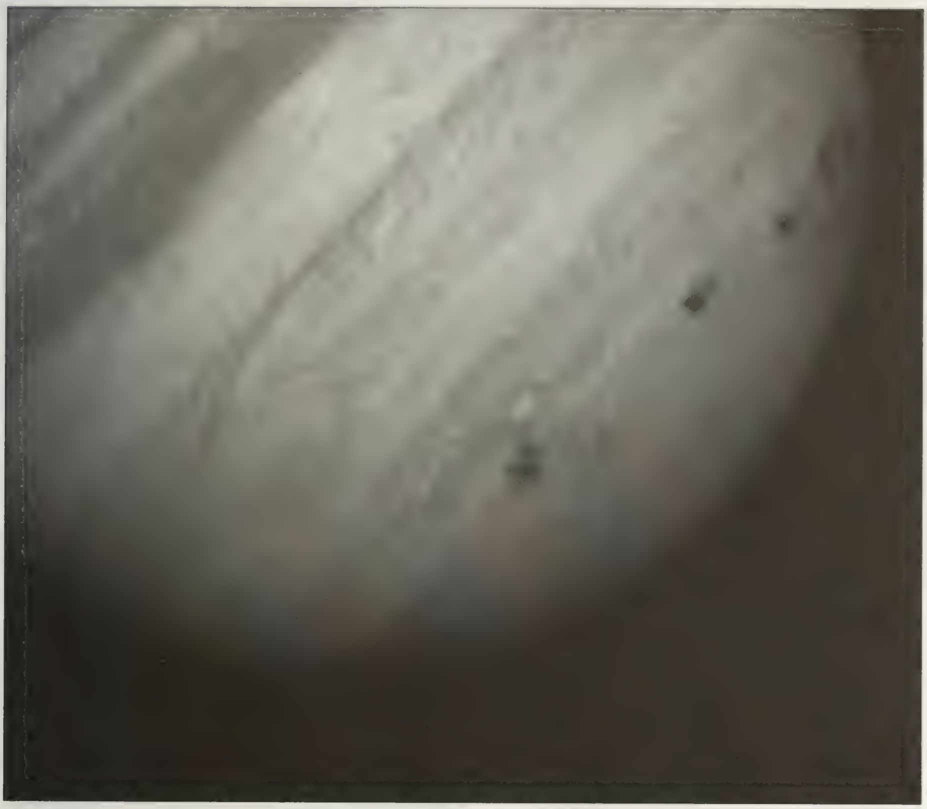

Figure 4–23. Image of Jupiter with Hubble's Wide Field and Planetary Camera 2. Eight impact sites are visible. (STScI-PRC1994-34. Hubble Space Telescope Comet Team and NASA)

Cosmic Collision. Observations of Supernova 1987A, the closest supernova in four centuries, provided details for the first time on the interaction of a blast wave from a supernova with its surrounding environment. The three-ring structure was an unexpected feature. The set of images in figure 4–26 shows Supernova 1987A and its neighborhood.

Probing Stars in Dense Regions. The Hubble Space Telescope's superb resolution was a major asset when observing dense stellar environments. The telescope produced many results on resolved stellar populations in globular clusters (galactic and in the Local Group), in field populations of nearby galaxies, and in stellar aggregates (clusters) in the Magellanic clouds. Figure 4–27 shows a view of the G1 globular cluster captured by the Hubble Space Telescope.

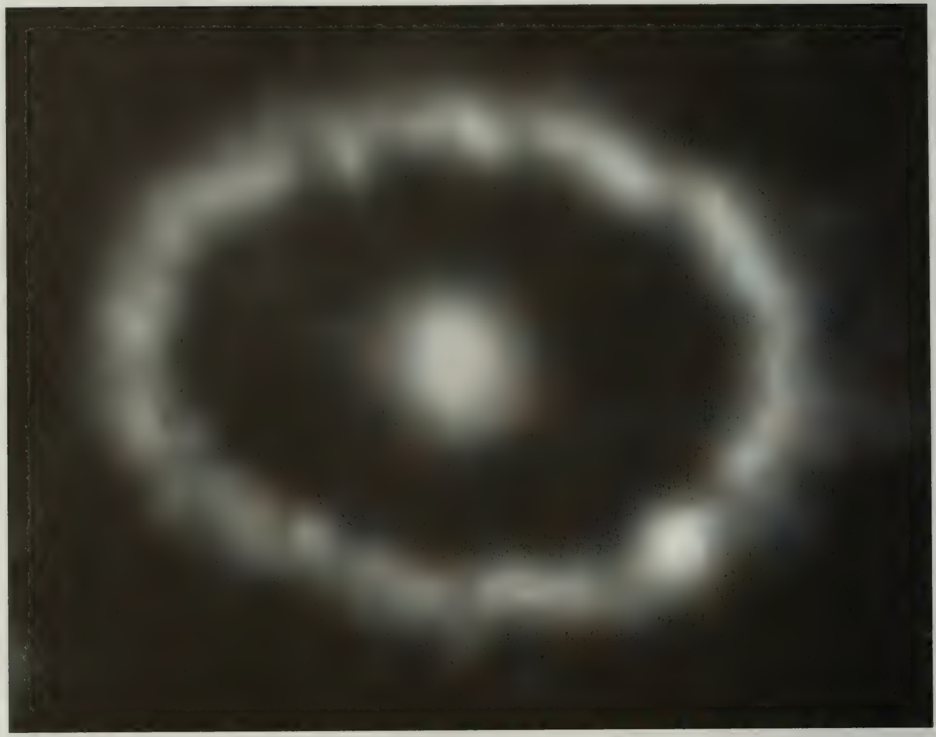

Figure 4–24. Ring Structure Around Supernova 1987A, February 6, 1996. (STScI 2004-09. NASA, P. Challis, R. Kirschner (Harvard-Smithsonian Center for Astrophysics) and B. Sugerman (STScI))

Hubble Space Telescope results included the following:

- The spread of ages among galactic globulars was relatively narrow, implying a short timescale for the formation of spheroidal components of galaxies.
- The horizontal branch morphology was determined in globulars as far as in M31 and M33, providing clues about the formation age of globulars in the Local Group.
- The first-time revelation of the sequence of cooling white dwarfs in several nearby globulars and exploration of the bottom of the main sequence.
- Star formation histories of resolved dwarf galaxies exhibited a wide variety of behaviors.
- Valuable information on star formation and the Initial Mass Function in the Magellanic clouds. This data suggests important implications for star formation in the early universe, a universe deficient in the heavier elements.

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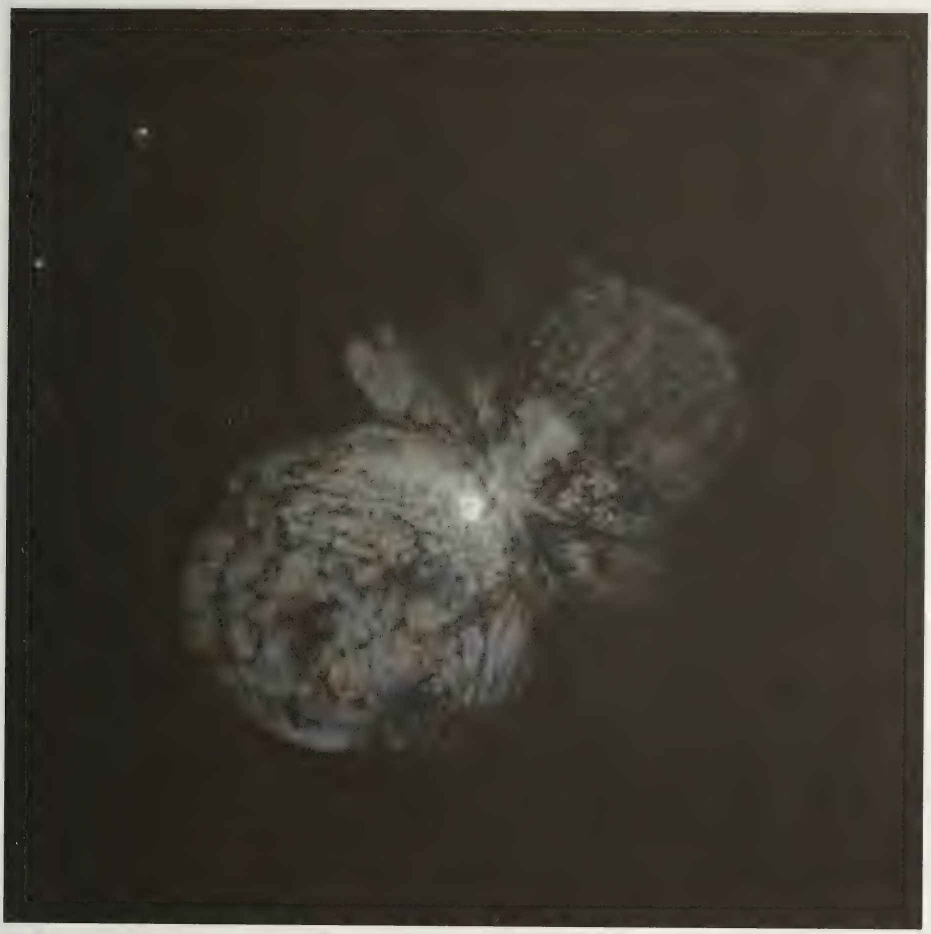

Figure 4–25. Hubble's Wide Field and Planetary Camera 2 observed Eta Carinae in September 1995. Images taken with red and near-infrared filters were subsequently combined to produce this color image. A sequence of eight exposures was necessary to cover the object's huge dynamic range. A giant outburst about 150 years ago produced two bipolar lobes, visible in this image. Estimated to be 100 times more massive than our Sun, Eta Carinae may be one of the most massive stars in our galaxy. It radiates about 5 million times more power than our Sun. (STScI-PRC1996-23a)

Black Holes a Common Occurrence. In the dense environments of galactic centers, the Hubble Space Telescope confirmed previous suspicions and provided decisive evidence showing that supermassive black holes resided in the centers of many (not necessarily active) galaxies. High-resolution images revealed the presence of dusty gas tori around the central object. The ability to spectroscopically determine velocities at multiple locations led to reliable determinations of the black hole masses. Figure 4–28 shows three black holes discovered by the Hubble Space Telescope.

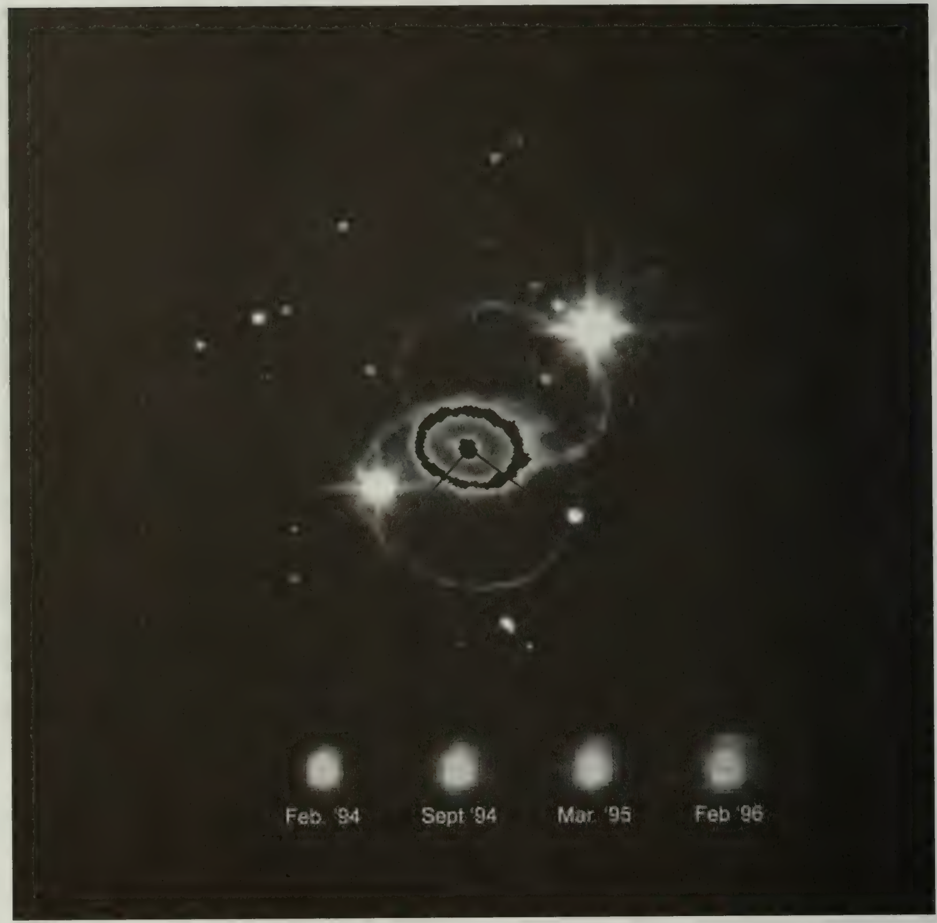

Figure 4–26. This image, taken by Hubble Space Telescope's Wide Field and Planetary Camera 2, shows the evolution of Supernova 1987A debris from February 1994 to February 1996. Material from the stellar interior was ejected into space during the supernova explosion in February 1987. The explosion debris was expanding at nearly 6 million miles per hour. (STScI-PRC1997-03. Chun Shing Jason Pun (NASA/GSFC), Robert P. Kirschner (Harvard-Smithsonian Center for Astrophysics), and NASA)

Galaxy Collisions. In the violent environment of colliding galaxies, the Hubble Space Telescope showed that young, massive, compact star clusters were formed when two galaxies collided or interacted strongly. The formation time was of the order of 10 million years or less, and these clusters might be the progenitors of globular clusters. Figure 4–29 shows the fireworks accompanying colliding galaxies. The Hubble Space Telescope has uncovered more than 1,000 bright young star clusters bursting to life as a result of galaxy collusions.

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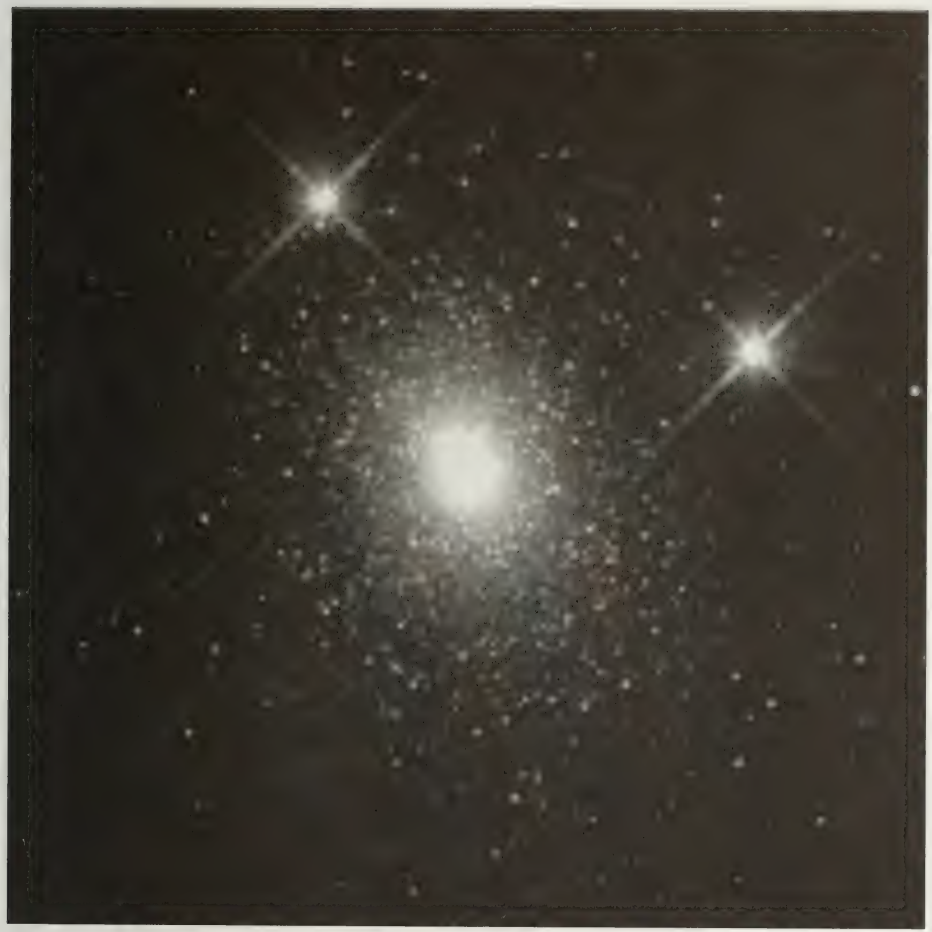

Figure 4–27. This globular cluster, called G1, orbits the Andromeda galaxy (M31), the nearest major spiral galaxy to our Milky Way. Located 130,000 light-years from Andromeda's nucleus, G1 is the brightest globular cluster in the Local Group of galaxies. The Local Group consists of about 20 nearby galaxies, including the Milky Way. (STScI-PRC1996-11. Michael Rich, Kenneth Mighell, and James D. Neill (Columbia University) and Wendy Freedman (Carnegie Observatories) and NASA)

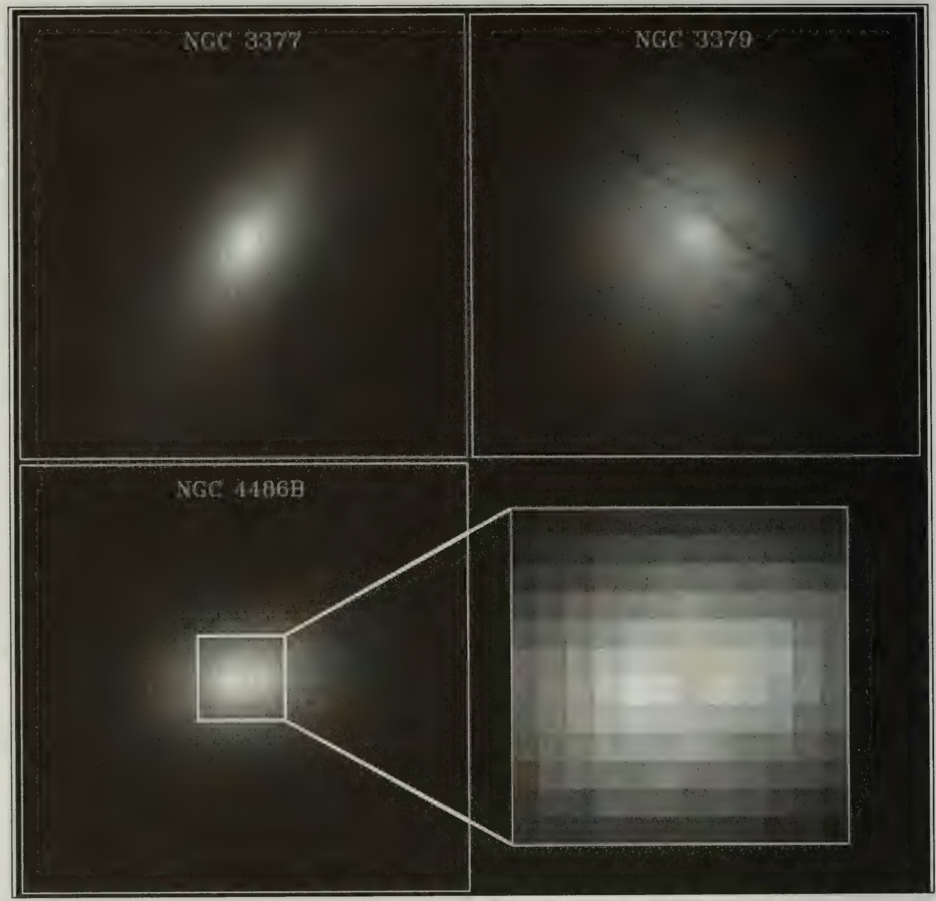

Figure 4–28. Announcing the discovery of three black holes in three normal galaxies in January 1997, astronomers suggested that nearly all galaxies may harbor supermassive black holes once powering quasars but now quiescent. The conclusion was based on a census of 27 nearby galaxies carried out by the Hubble telescope and ground-based observatories in Hawaii. (STScI-PRC1997-01. Karl Gebhardt, University of Michigan; Tod Lauer, National Optical Astronomy Observatory; and NASA)

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Host Galaxies for Quasars. Findings from ground-based observations previously suggested that quasars reside in host galaxies; the Hubble Space Telescope confirmed this. And with superb resolution, the telescope demonstrated that a high fraction of the hosts are interacting galaxies. This information could be an important clue for how the central black hole is fed. Astronomers believe a quasar turns on when a massive black hole at the nucleus of a galaxy feeds on gas and stars. As the matter falls into the black hole, intense radiation is emitted. Eventually, the black hole stops emitting radiation when it consumes all nearby matter. Then it needs debris from a collision of galaxies or another process to provide more fuel. Figure 4–30 shows examples of different home sites of quasars.

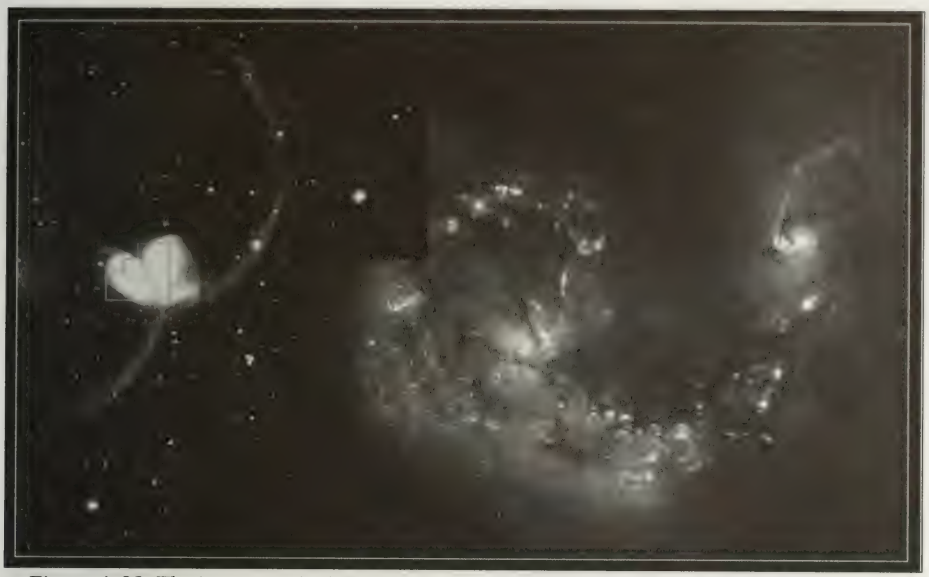

Figure 4–29. The image on the left shows two galaxies, called the Antenna. The green shape pinpoints the Hubble Space Telescope's view. The Hubble Space Telescope's close-up view on the right shows the "fireworks" at the center of the collision. The sweeping spiral-like patterns, traced by bright blue star clusters, result from a firestorm of star birth triggered by the collision. (STScI-PRC1997-34a. Brad Whitmore, STScI, and NASA)

An Expanding Universe. Ever since Edwin Hubble's discovery of the expansion of the universe in the late 1920s, measuring the value of the Hubble constant (indicative of the rate at which the universe is expanding and the age of the universe) was a prime target for observational cosmology. In May 1999, a Hubble Space Telescope project team announced the completion of a program aimed at measuring the distances to 18 galaxies, some as far as 20 megaparsecs away (in the Virgo cluster galaxies). By measuring the distance to the Cepheid variables in the Virgo clusters by a variety of methods, astronomers could reach a more accurate value for the Hubble constant, arriving at a value of 70 kilometers (43 miles) per second per megaparsec for the Hubble constant, with an uncertainty of about 10 percent. This project would have been impossible without the Hubble Space Telescope's resolution and depth. By calibrating the absolute magnitudes at maximum of a sample of Type Ia supernovae, another team determined the distances to galaxies in the Hubble flow, finding a value of 60 kilometers (37 miles) per second per megaparsec (with a 10 percent uncertainty) for the Hubble constant. Thus, the discrepancy among the values determined by different groups (and different methods) was finally being resolved. Before the Hubble Space Telescope, scientists placed the age of the universe at anywhere between 10 billion and 20 billion years; using the telescope, they agreed that approximately 12 billion to 15 billion years had elapsed since the Big Bang. Figure 4–31 shows spiral galaxy NGC 4603, the most distant galaxy in which Cepheid variables were found.

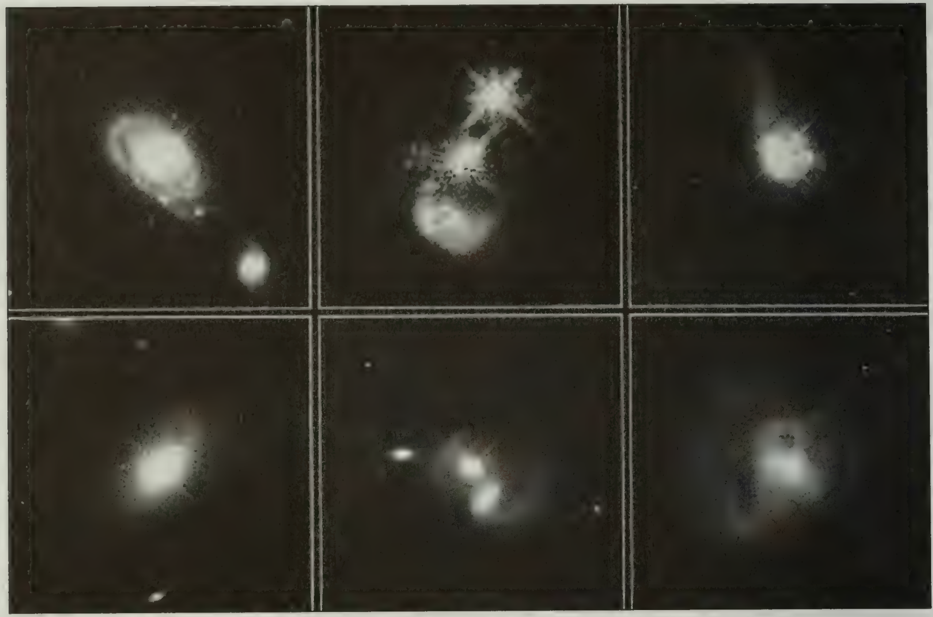

Figure 4–30. Quasar Host Galaxies. The column on the left represents normal galaxies, the center, colliding galaxies, and the right, peculiar galaxies. (PRC96-35a)

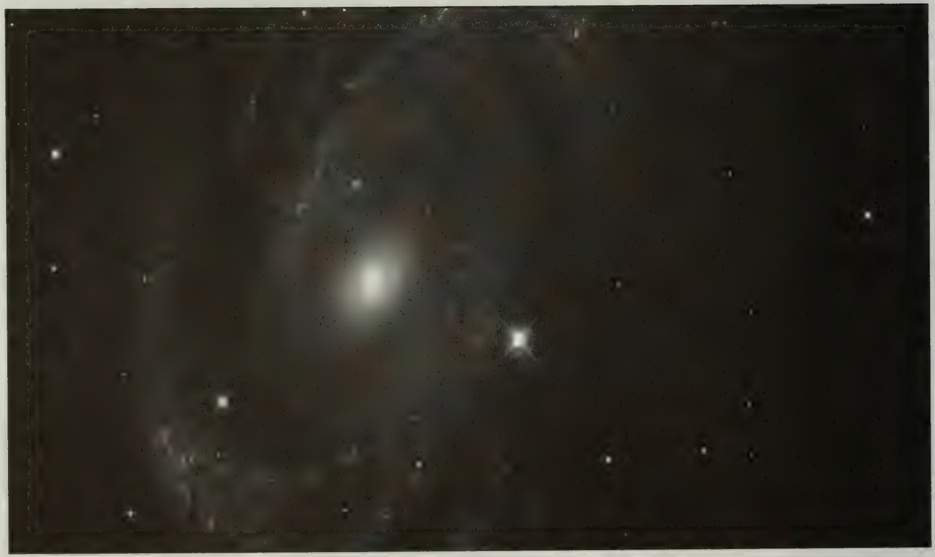

Figure 4–31. Spiral galaxy NGC 4603, the most distant galaxy in which a special class of pulsating stars, called Cepheid variables, have been found. The Hubble Space Telescope's Wide Field and Planetary Camera was used to observe this galaxy. (STScI-PRC1999-19. J. Newman University of California, Berkeley, NASA)

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Cosmic Explosions. The Hubble Space Telescope teamed up with x-ray and gamma-ray satellites, as well as with ground-based optical telescopes, to understand gamma-ray burst sources. Gamma-ray bursts may represent the most powerful explosions in the universe since the Big Bang. Before 1997, astronomers were frustrated because, although more than 2,000 bursts had been observed, it was impossible to determine whether these fireballs occurred in our own galaxy's halo or at cosmological distances. The discovery of x-ray afterglows by the BeppoSAX satellite, followed by the discovery of optical transients (from the ground), led to a confirmation of the cosmological nature of at least a subclass of bursts. The telescope provided images showing unambiguously that gamma-ray bursts actually reside in galaxies that were forming stars at high rates. Furthermore, by pinpointing a burst's precise location, the Hubble Space Telescope showed that, at least in one case, the gamma-ray burst was probably not associated with an active galactic nucleus. Figure 4–32 shows a gamma-ray burst's visible light component.

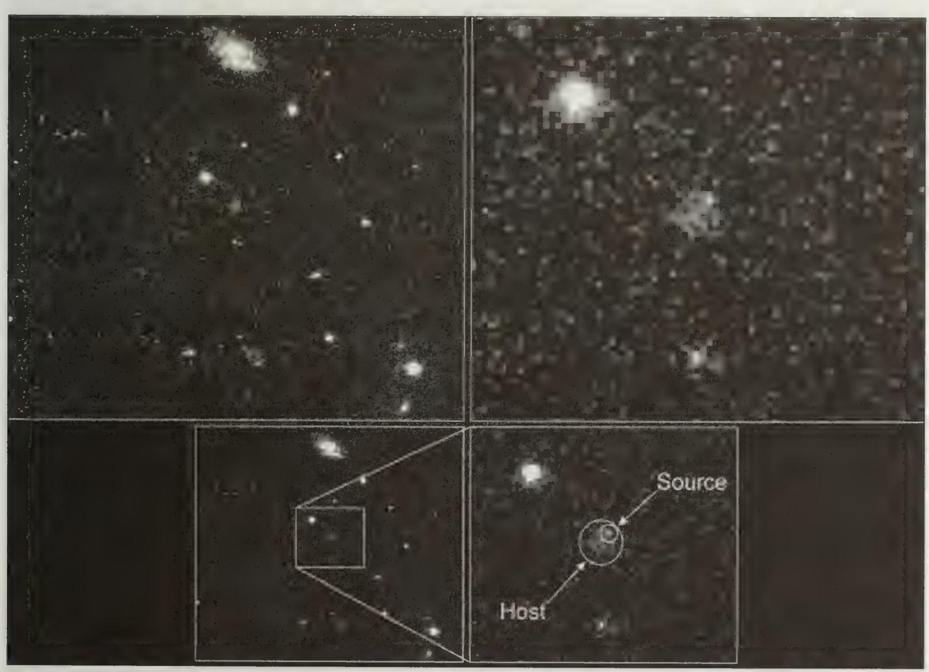

Figure 4–32. This image of gamma-ray burst GRB 970228 was acquired with the Space Telescope Imaging Spectrograph. In it, the fireball has faded to 1/500th its brightness since its discovery in March 1997 by ground-based telescopes. The Hubble Space Telescope continues to clearly see the fireball (center of picture) and a cloud of material surrounding it, considered to be its host galaxy. (PRC97-30. A. Fruchter, STScI, and NASA)

Cosmic Expansion Accelerating. In 1998, two teams independently found strong evidence that cosmic expansion was accelerating. This conclusion, based on distance measurements to Type Ia supernovae (if confirmed), also implied the existence of a cosmological constant, which contributed about 70 percent of the cosmic energy density. While many of the observations were made with the Keck telescope, the Hubble Space Telescope provided the resolution needed for the high-redshift supernovae, supernovae with light needing to be distinguished from that of the host galaxies. The Hubble Space Telescope's contribution was crucial in establishing that the more distant Type Ia supernovae are dimmer (by about 0.25 magnitude) than expected from the Hubble Law. Figure 4–33 shows Hubble Space Telescope images of three distant supernovae, stars which exploded and died billions of years ago.

Compton Gamma Ray Observatory

The CGRO was NASA's second orbiting Great Observatory. At more than 17 tons, the CGRO was the heaviest astrophysical payload ever flown at time of launch. The CGRO was the first satellite dedicated to observing gamma rays across a broad spectrum of energies. Scientists believe gamma rays are emitted during violent cosmic events, such as the formation of supernovae, quasars, and pulsars, and near black holes. NASA scientists used the CGRO to create a comprehensive map of celestial gamma-ray sources.[115]

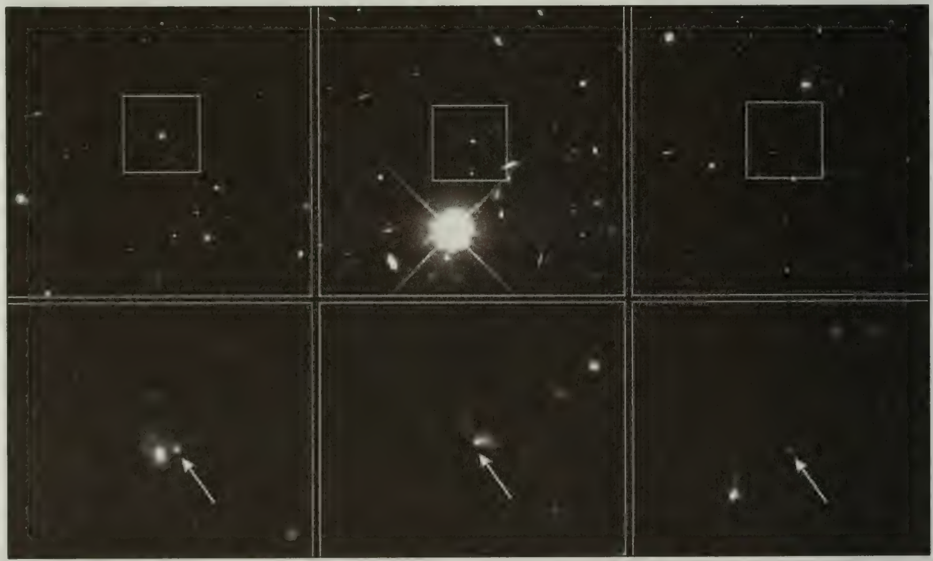

Figure 4–33. These images of distant supernovae, stars that exploded and died billions of years ago, were taken with the Hubble Space Telescope's Wide Field and Planetary Camera 2. Scientists use these faraway light sources to estimate if the universe was expanding at a faster rate long ago and is now slowing down. (PRC1998-02. P. Garnavich, Harvard-Smithsonian Center for Astrophysics, and NASA)

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[115] Donna Drelick, "Compton Gamma Ray Observatory On Orbit Five Years," *Goddard News* 43 (April 1996): 3.

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The project began in August 1977, when NASA released an announcement of opportunity for the Gamma Ray Observatory. In 1981, NASA selected TRW Inc. as the GRO contractor. Fabrication of flight components took place during 1985–1987, and in 1986, the GRO was designated a "Great Observatory." Detector module assembly took place during 1986–1988, and instrument integration during 1988–1989. The completed observatory was shipped to Kennedy Space Center in February 1990, to make final preparations for an April 1991 launch. On STS-37, the CGRO was launched April 5, 1991 on STS-37 aboard the Space Shuttle *Atlantis* and deployed on April 7 (see Figure 4–34). NASA renamed the observatory the Compton Gamma Ray Observatory on September 23, 1991, in honor of Dr. Arthur Holly Compton, winner of the Nobel Prize in physics for work on scattering of high-energy photons by electrons. This process was central to the gamma-ray detection techniques of all four of the observatory's instruments.

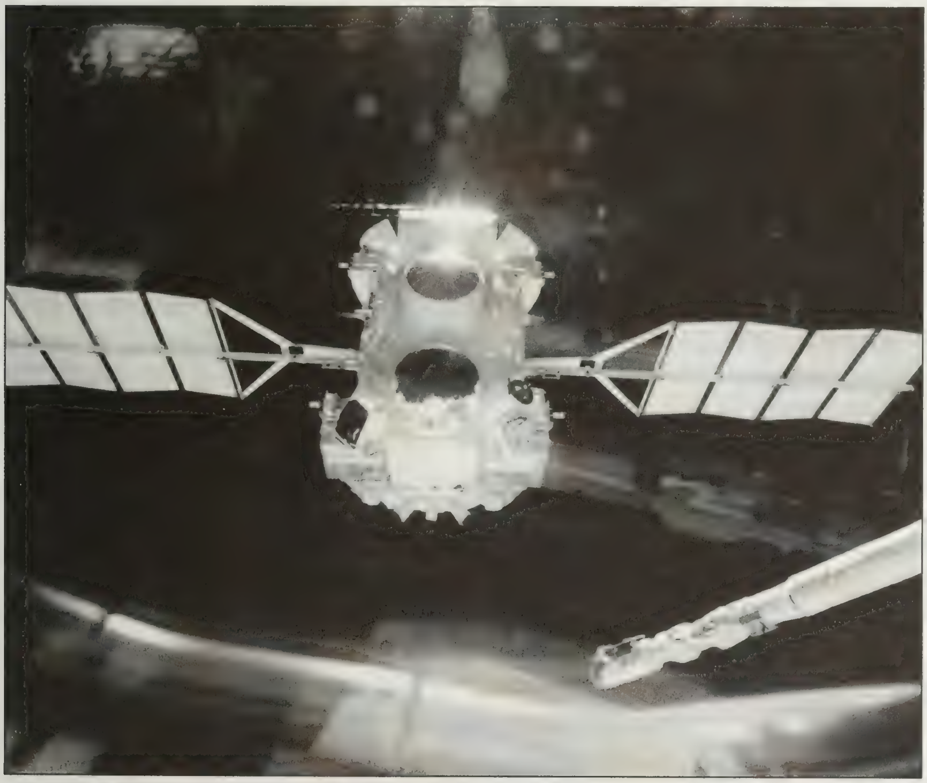

Figure 4–34. The Shuttle Atlantis *Remote Manipulator System releases the GRO during STS-37 deployment. Visible on the GRO as it drifts away from the robotic arm are its four instruments: the Energetic Gamma Ray Experiment (bottom), Imaging Compton Telescope (center), Oriented Scintillation Spectrometer Experiment (top), and Burst and Transient Source Experiment (at four corners). The GRO's solar array panels are extended and are in orbit configuration. The photo was taken through the aft flight deck window, which reflects some of the crew compartment interior. (NASA Photo No. STS-37-96-009)*

The CGRO was a NASA cooperative program. Germany had PI-responsibility for the Energetic Gamma Ray Experiment Telescope (EGRET), along with scientists at Goddard Space Flight Center, Stanford University, and Grumman Aerospace.[116] Germany also furnished hardware elements and provided co-investigator support for a second instrument, the imaging Compton Telescope (COMPTEL), developed as a joint venture of Germany, the Netherlands, the ESA, and the United States. Scientists at Marshall Space Flight Center developed the Burst and Transient Source Experiment (BATSE), and the U.S. Naval Research Laboratory developed the Oriented Scintillation Spectrometer Experiment (OSSE).

Dedicated to observing the high-energy universe, the CGRO was the heaviest astrophysical payload flown to date, weighing 35,000 pounds (15,875 kilograms) or 17.5 tons. The CGRO instruments alone weighed approximately 6 tons (5,400 kilograms) and were much larger and more sensitive than those on any gamma-ray telescope previously flown in space. The observatory's four instruments together detected a broad range of gamma rays. Their large size was necessary because the number of gamma-ray interactions that could be recorded was directly related to the mass of the detector. The number of gamma-ray photons from celestial sources was very small when compared to the number of optical photons. Large instruments were needed to detect a significant number of gamma rays in a reasonable amount of time. The combination of these instruments detected photon energies from 20,000 electron volts to more than 30 billion electron volts.[117] For each instrument, an improvement in sensitivity of more than a factor of 10 was realized compared to previous missions.[118] Figure 4–35 shows the location of the CGRO's instruments.

The CGRO mission objectives were to measure universe gamma radiation and to explore the fundamental physical processes powering this radiation. The following were the CGRO's observational objectives:

- Search for direct evidence of the synthesis of the chemical elements.
- Observe high-energy astrophysical processes occurring in supernovae, neutron stars, and near black holes.
- Locate gamma-ray burst sources.
- Measure the diffuse gamma-ray radiation for cosmological evidence of its origin.
- Search for unique gamma-ray-emitting objects.

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[116] "Compton Gamma Ray Observatory: Exploring the Mysteries of Time," NASA Facts On-Line, NASA Goddard Space Flight Center, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/gro.htm* (accessed September 1, 2005).

[117] "About the Compton Gamma Ray Observatory," *http://heasarc.gsfc.nasa.gov/docs/cgro/cgro/* (accessed May 15, 2006).

[118] "NASA's Great Observatories," *http://www.nasa.gov/audience/forstudents/postsecondary/features/F_NASA_Great_Observatories_PS.html* (accessed May 15, 2006).

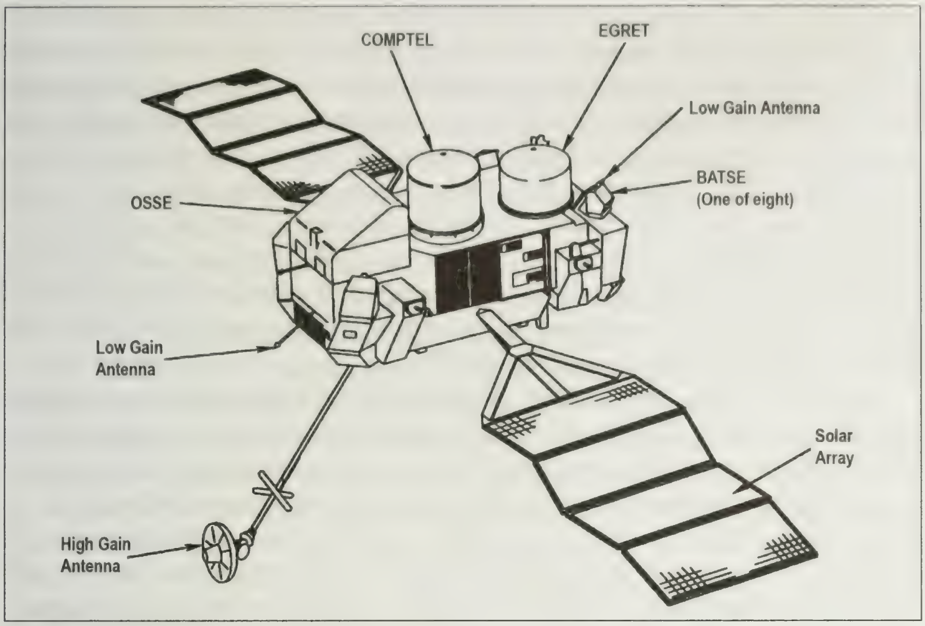

Figure 4–35. Compton Gamma Ray Observatory.

The observatory's scientific agenda included studies of the following energetic celestial phenomena: solar flares, cosmic gamma-ray bursts, pulsars, nova and supernova explosions, accreting black holes of stellar dimensions, quasar emission, and interactions of cosmic rays with the interstellar medium.[119]

The three-axis stabilized spacecraft had a zero momentum biased control system that used reaction wheels. Two solar arrays generated 4,500 watts of power (beginning of life), supplemented by three 50 Ahr nickel cadmium batteries. The hydrazine propulsion system carried 1,900 kilograms (4,198 pounds) of fuel with four 100-pound-force (445-newton) thrusters and eight 5-pound-force attitude control system thrusters. The S-band telecom system provided uplink at 1 kbps and downlink via the TDRS System at 256 kbps to 512 kbps. The S-band telecom system's 1.52-meter (5-foot) high-gain antenna was mounted on a 4.4-meter (14.4-foot) boom.

The CGRO operated successfully for nine years. During this period, the observatory's achievements were unprecedented, as discoveries of phenomena never before seen led scientists to gain new insights and pose more questions. The CGRO's instruments, taking advantage of a "target of opportunity," made the most sensitive, high-energy measurements ever of the Sun, gathering data from two X-class solar flares, the largest and most powerful type of solar flare.[120] The BATSE detected gamma-ray bursts at a higher rate and in more detail than ever before.[121] After less than four months in space, the EGRET detected the most distant and luminous gamma-ray source ever seen, a quasar emitting a large flux of gamma rays, gamma rays with photon energies greater than 100 million electron volts. The luminosity or total energy emitted by the quasar was approximately 10 million times that of the total emission of the Milky Way. The quasar was a variable quasar, meaning that its intensity changed over time. The source should have been visible to two previous gamma ray missions during 1972–1973 and 1975–1982, according to the EGRET PI, but neither previous mission reported detection. Between 1982 and 1991, this quasar went from being undetectable to being one of the few, brightest objects in the gamma-ray sky. [122]

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[119] Rumerman, *NASA Historical Data Book, 1979–1988, Volume V,* pp. 404–406. Also "Universe Missions," *http://science.hq.nasa.gov/missions/universe.html* (accessed May 16, 2006).

[120] John J. Loughlin II, "Gamma Ray Observatory Grabs Target of Opportunity," *Goddard News* 37 (July 1991): 1.

In August 1991, the satellite detected 117 gamma-ray bursts scattered throughout the sky. These were violent bursts coming from a location in the sky where there was no known source of x-rays or gamma rays. The outbursts were thought to originate in binary star systems containing an ordinary star in orbit with a highly compact star, either a neutron star or black hole. The outbursts were believed to be triggered when a large amount of material was suddenly released from a normal star and fell through the intense gravitational field of a compact star to its surface.[123] A few months later, on January 31, 1992, the EGRET detected the largest gamma-ray bursts yet; these "virtually blinded" its instruments. Dubbed the "Super Bowl burst," it was 10 times more energetic than any previous burst, more than 100 times brighter at its peak than the brightest steady source of gamma rays in the Milky Way, and more than 1,000 times brighter than any other known sources outside the Milky Way.[124] Data also indicated the possible occurrence of bursts much deeper in space than many had believed, far beyond the Milky Way galaxy. A two-year BATSE mapping survey showed that the bursts were evenly distributed in space, indicating they may have originated outside our galaxy.[125]

In 1993, the COMPTEL made three major discoveries. The instrument detected two radioactive isotopes, titanium 44 and aluminum 26 emissions. When these isotopes decayed, they left interstellar trails, called gamma-ray lines, which COMPTEL scientists traced to the supernovae that produced the emissions long ago. The third discovery identified the Orion nebula, an area of molecular clouds and star-forming regions, as a source of cosmic rays. Cosmic rays were discovered in 1911, but their source has eluded scientists.[126]

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[121] "NASA Science Instrument Observing Gamma-Ray Bursts," *NASA News* Release 91-81, May 28, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-081.txt* (accessed September 1, 2005).

[122] "NASA Observatory Detects Strongest Gamma Ray Source," *NASA News* Release 91-117, July 25, 1991, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1991/91-117.txt* (accessed September 1, 2005).

[123] "Compton Observatory Discovers New Energy Source," *Goddard News* 39 (September 1992): 4.

[124] "Findings Burst Gamma Ray Theories," *HQ Bulletin* (May 3, 1993): p. 3. Also, Michael Finneran, "NASA Satellite Shakes Theories on Gamma-Ray Bursts," *Goddard News* 40 (May 1993): 5.

[125] Finneran, "NASA Satellite Shakes Theories on Gamma-Ray Bursts," *Goddard News* 40 (May 1993): 5.

[126] "Gamma-Ray Observatory Produces Three Major Discoveries," *NASA News* Release 93-182, October 12, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-182.txt* (accessed September 1, 2005).

In early 1994, astronomers uncovered new evidence of gamma-ray bursts occurring in the far reaches of the universe. Evidence indicated that the gamma-ray bursts showed relative "time dilation," an effect created by many of the bursts occurring so far away in the universe that time appeared to run slower in those far regions. Time dilation was a consequence of the general theory of relativity and the expansion of the universe. Thus, time intervals from very distant parts of the universe would be stretched as the gamma-ray bursts made their way across the expanse of space, which itself was expanding.[127]

On July 27, 1994, the BATSE detected an unusually bright x-ray source in the southern constellation Scorpius. Named X-ray Nova Scorpii, or GRO J1655-40, its x-ray emission rivaled those from two other sources, the Crab Nebula and Cygnus X-1. It also raised questions about how x-rays were produced in such objects.[128] The BATSE also detected indications of gamma-ray flashes above thunderstorms at a rate six times that of previous observations.[129]

In early December 1995, astronomers using the BATSE sighted a celestial object with sudden, violent eruptions unlike anything seen before. Since discovery, the "bursting pulsar," exploded more than 2,000 times in blasts of x-rays, becoming the brightest source of x-ray emissions in the sky. The object did several things at once, both pulsing like the energy surrounding a black hole and bursting explosively like a star. It also oscillated and flickered, emitting x-rays 1 million times the power of the Sun. Scientists expected the strange bursting pulsar to die out within two weeks or, at most, two months.[130]

By the end of 1995, scientists had recorded more than 1,400 gamma-ray bursts, spread evenly across the entire sky. The CGRO also completed a new survey of the highest energy gamma-ray sources, demonstrating that about half were quasars with beams of energy pointed directly toward Earth but leaving the other half unidentified.[131]

On September 24, 1996, the BATSE detected the brightest gamma-ray burst that the CGRO mission had experienced when high-energy gamma radiation in the form of a colossal cosmic gamma-ray burst bombarded the BATSE's eight detectors. This burst was the most intense that the BATSE had observed.[132] The next month, the BATSE detected four separate gamma-ray bursts in two groups coming in close succession, all from the same part of the sky, with one burst lasting 23 minutes. This was puzzling because it differed from the typical detection rate of about one gamma-ray burst per day lasting about 10 to 30 seconds and randomly distributed across the sky.[133]

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[127] "Satellite Finds Imprint of Universe on Gamma-Ray Explosions," *NASA News* Release 94-10, January 15, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-010.txt* (accessed September 1, 2005).

[128] "Compton Gamma-Ray Observatory Finds Bright New X-ray Source," *NASA News* Release 94-140, August 24, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-010.txt* (accessed September 1, 2005).

[129] "Gamma Ray Flashes in Atmosphere More Common Than Thought," *NASA News* Release 94-204, December 7, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-204.txt* (accessed September 1, 2005).

[130] "Bursting Pulsar Is 'One Man Band,'" *HQ Bulletin*, (March 18, 1996): p. 3.

[131] *Aeronautics and Space Report of the President, Fiscal Year 1995 Activities* (Washington, DC: National Aeronautics and Space Administration), p. 18.

[132] "NASA Spacecraft Detects the Brightest Gamma-Ray Burst of Its Mission," Space Science Features, Marshall Space Flight Center (September 26, 1996), *http://science.nasa.gov/newhome/headlines/ast26sep96_1.htm* (accessed September 1, 2005).

In April 1997, scientists announced the discovery of two unexpected clouds of antimatter in the Milky Way, which scientists called "antimatter annihilation radiation." The discovery, made with the OSSE, pointed to the existence of a hot fountain of gas filled with antimatter electrons rising from a region surrounding the center of the Milky Way. The nature of the furious activity producing the hot antimatter-filled fountain was unclear but could be related to massive star formation taking place near the large black hole at the center of the galaxy.[134]

On December 14, 1997, both the Italian-Dutch BeppoSAX satellite and CGRO detected a massive cosmic gamma-ray burst releasing one hundred times more energy than previously theorized, making it the most powerful explosion observed since the creation of the universe. The burst appeared to have released several hundred times more energy than an exploding star, until then the most energetic known phenomenon in the universe. Finding a large energy release during a brief period of time was unprecedented in astronomy, except for the Big Bang itself. Originating in a faint galaxy, scientists measured the release's distance at about 12 billion light years from Earth. The CGRO provided detailed measurements of the total brightness of the burst, designated GRB 971214, while BeppoSAX provided its precise location, enabling follow-up observations using ground-based telescopes and the Hubble Space Telescope.[135]

In June 1998, the BATSE on the CGRO and the Rossi X-ray Timing Explorer registered a series of bursts coming from a Soft Gamma Repeater (SGR), a neutron star emitting bursts of soft or low-energy gamma rays at irregular intervals. Unlike most one-time gamma-ray bursts, scientists believed SGRs to be just one short phase in the life of a magnetar, a neutron star with an extremely powerful magnetic field. If correct, SGR outbursts were caused by massive starquakes as the magnetic field wrinkled the star's crust—wrinkles only a few millimeters high but releasing more energy than all the earthquakes Earth had ever experienced. The new SGR triggered the BATSE 26 times during June 15–22, including 12 bursts on June 18. Each burst lasted 0.2 seconds, typical for an SGR. Another five bursts from the same area of the sky were recorded on June 17 and June 18, with the last burst peaking at almost 500,000 counts per second, making for a powerful source.[136]

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[133] "Astronomers Detect Never Before Seen Gamma-Ray Multi-Bursts," *NASA News* Release 96-261, December 17, 1996, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1996/96-261.txt* (accessed September 1, 2005).

[134] "Antimatter Clouds and Fountain Discovered in the Milky Way," *NASA News* Release 97-23, April 28, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-083.txt* (accessed September 1, 2005).

[135] "Most Powerful Explosion Since the Big Bang Challenges Gamma Ray Burst Theories," Goddard Space Flight Center Release 98-052 (HQ 98-75), May 6, 1998, *http://www.gsfc.nasa.gov/news-release/releases/1998/98-052.htm* (accessed August 29, 2005).

[136] "A Whole Lot of Shakin' Going On: Starquakes Lead To Discovery of First New Soft Gamma Repeater in 19 Years," Science@NASA, *http://science.nasa.gov/newhome/headlines/ast09jul98_1.htm* (accessed September 1, 2005).

To keep the CGRO in the correct orbit so it did not reenter Earth's atmosphere, the satellite received scheduled boosts to higher orbits. These boosts were necessary to compensate for orbit decay from the effect of solar activity on the ionosphere, which increased the atmospheric drag on the spacecraft and slowly pushed it toward Earth. The first reboost was accomplished in two phases: one ended in October 1993, and the second spanned November and December 1993. The October boost lifted the observatory's apogee to 280 miles (452 kilometers) from 214 miles (346 kilometers). The November-December boost nudged the spacecraft's perigee to 280 miles, making its orbit around Earth almost perfectly circular. The reboost extended the mission life of the observatory by five years.[137]

A second reboost took place in 1997 over a two-month period ending on June 3, 1997. Before the reboost, which included several rocket burns per week, the CGRO's altitude had slipped to 440 kilometers (273 miles) above Earth. The reboost raised the altitude to 515 kilometers (320 miles). Project scientists stated that this reboost would keep the satellite in orbit until perhaps 2007.[138]

Although the 1997 reboost allowed for possible continuation in orbit until 2007, gyroscope No. 3 began experiencing problems in 1999, and NASA engineers began planning for the observatory's reentry into Earth's atmosphere. NASA chose a controlled deorbit of the spacecraft because of safety concerns. The spacecraft was too large and heavy to burn up on reentry. When it reentered the atmosphere, large pieces most certainly would survive and hit Earth. Some pieces might be as large as 1 ton (907 kilograms) and might hit at 200 miles per hour (320 kilometers per hour). The debris field, or footprint, was estimated at approximately 16 miles wide by 962 miles long (26 kilometers by 1,552 kilometers).[139] NASA also feared that an uncontrolled reentry might occur over populated areas if an additional gyroscope failed. Edward Weiler, Office of Space Science Associate Administrator, stated that NASA estimated there was a one in ten thousand chance a human life could be lost if the spacecraft reentered the atmosphere on its own.[140]

The controlled reentry occurred over a remote region of the Pacific Ocean, after four engine burns between May 30 and June 4, 2000, which gradually lowered its orbit. The CGRO fell to Earth on June 4 after nine years in orbit. Debris landed in an area of ocean approximately 2,400 miles (3,962 kilometers) southeast of Hawaii.[141] See Table 4–49 for further mission details.

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[137] "NASA Succeeds With Gamma-Ray Observatory Reboost," *NASA News* Release 93-224, December 20, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-224.txt* (accessed August 31, 2005).

[138] "Successful Reboost of Compton Gamma Ray Observatory," CGRO Science Support Center, *http://cossc.gsfc.nasa.gov/docs/cgro/epo/news/reboost.html* (accessed September 1, 2005).

[139] "Goddard Team Prepares To Deorbit CGRO," *Goddard News* (May 26, 2000), *http://www.gsfc.nasa.gov/ftp/gnewsissues/052600/052600.htm* (accessed August 31, 2005).

[140] Keith Cowing "Compton Gamma Ray Observatory Crashes on Earth," SpaceRef.com, *http://www.spaceref.com/news/viewnews.html?id=153* (accessed August 31, 2005).

[141] "Compton Gamma Ray Observatory Safely Returns to Earth," Final Status Report: June 4, 2000, *ftp://ftp.hq.nasa.gov/pub/pao/media/2000/CGRO_status_final_06-04.txt* (accessed August 31, 2005). Also, Cowing "Compton Gamma Ray Observatory Crashes on Earth," SpaceRef.com, *http://www.spaceref.com/news/viewnews.html?id=153* (accessed August 31, 2005).

Advanced X-ray Astrophysics Facility

The AXAF, renamed Chandra in December 1998, was NASA's third Great Observatory. Launched on STS-93 *Columbia* on July 23, 1999, the spacecraft's development took place during a 20-year period. This observatory covers the x-ray portion of the electromagnetic spectrum, observing such objects as black holes, quasars, and high-temperature gases.

Two astrophysicists, Riccardo Giacconi and Harvey Tananbaum, proposed the AXAF to NASA in 1976. The project received funding in 1977, and preliminary work began at Marshall Space Flight Center and the SAO in Cambridge, Massachusetts.[142] At the same time, Marshall Space Flight Center was preparing to launch the first High Energy Astronomy Observatory (HEAO-1) that gave scientists their best views to date of the universe in x-rays, gamma rays, and cosmic radiation. The next spacecraft in the series, HEAO-2, was launched in 1978. (HEAO-2 was also called the Einstein Observatory because it was launched during the centennial year of Albert Einstein's birth.) HEAO-2, the predecessor to AXAF, was the first imaging x-ray telescope and provided the first true images of x-ray-emitting objects.[143]

Design and development of AXAF began in the early 1980s with advanced technology development contracts to Perkin-Elmer and Itek Corporation to develop advanced x-ray mirrors. In 1984, NASA solicited, received, and reviewed, proposals for scientific instrument development.[144] In March 1985, NASA announced the selection of the scientific investigators whose projects would be included on the proposed AXAF. Those selected included instrument PIs to design and fabricate scientific instrumentation for placement in the telescope focal plane, interdisciplinary scientists to provide expertise on x-ray astrophysics and other fields of astronomy, and a telescope scientist to guide telescope fabrication. The investigators, as members of the AXAF science working group, would provide scientific and technical guidance throughout the project and would receive a specified amount of time to use the telescope during its first 30 operational months.[145]

In January 1988, NASA released a proposal to select a prime contractor for the AXAF, envisioned as a long-duration scientific satellite—the third of NASA's projected orbiting Great Observatories. The proposal was for a satellite to be serviced by Space Shuttle or Space Station crews. The AXAF would study high-energy emissions associated with quasars, spinning neutron stars, and black holes, providing valuable information about these phenomena

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[142] “"CXC Biographies: Dr. Harvey Tananbaum, Director, Chandra X-ray Center," *http://chandra.harvard.edu/press/bios/tananbaum_bio.html* (accessed April 26, 2006).

[143] "History of the Chandra X-Ray Observatory," *http://www.spacetoday.org/DeepSpace/Telescopes/GreatObservatories/Chandra/ChandraHistory.html* (accessed September 28, 2005).

[144] *Aeronautics and Space Report of the President, 1984 Activities*, (Washington, DC: National Aeronautics and Space Administration, 1985), p. 17.

[145] *Astronautics and Aeronautics, 1985; A Chronology*, (Washington, DC: National Aeronautics and Space Administration Special Publication-4025, 1988), pp. 39–40.

and serving as an important new tool for basic research in plasma physics. The AXAF would collect data on the various forms of "dark matter" in the universe, which might help investigators determine whether the universe was an open or closed loop. At the time, launch was foreseen to occur as early as 1995. The orbiting observatory would be 14 feet (4.3 meters) in diameter, 45 feet (13.7 meters) long, and would weigh 12 tons to 15 tons (10,886 kilograms to 13,608 kilograms). The observatory would be placed into a circular orbit 320 miles above Earth and would operate for about 15 years.[146]

In spring of 1988, Congress authorized the AXAF as a "new start" in NASA's FY 1989 budget, formally moving the program out of the preparatory stage into design and development. During the first year, work focused on developing the high resolution mirror assembly that would focus the x-rays on a complement of scientific instruments.[147] A specially designed x-ray calibration facility was constructed to assure the mirrors met design specifications.[148] In August 1988, NASA selected TRW, Inc. to be the prime contractor for AXAF construction and integration. TRW, Inc. had earlier been the prime contractor for the HEAO spacecraft.[149]

NASA selected the SAO in March 1991 to design, develop, and operate the science support center for the AXAF. The science support center would be the primary telescope focal point for the international science and observer community, The science support center would develop and oversee an observation program for the telescope and manage receipt and distribution of the collected data. The facility would also offer support during development of the telescope and its instruments for testing and verification of ground support systems, calibration of the instruments, and orbital operations relating to science instrument data.[150]

In 1992, in response to pressure to reduce costs, the AXAF was restructured. The restructured mission included two highly-focused smaller missions consisting of a large imaging spacecraft (AXAF-I) and a smaller spectroscopy spacecraft (AXAF-S) in place of the original single, larger observatory.[151] NASA reduced the number of mirrors on AXAF-I from twelve to eight and decided to use only four of the six proposed scientific instruments.[152] The planned orbit was changed from low to high Earth elliptical orbit to preserve the facility's scientific capability.[153] The orbit change meant that the AXAF could not be serviced by the Space Shuttle, and the change placed the observatory above Earth's radiation belts for most of its orbit. Experts estimated that the mission changes and elimination of maintenance costs and expenses of developing new instruments for later placement into the observatory would reduce development costs about $600 million and operating costs by an additional $1 billion.[154] In 1993, Congress directed the cancellation of the AXAF-S, the second smaller observatory.

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[146] *Astronautics and Aeronautics, 1986–1990; A Chronology,* (Washington, DC: National Aeronautics and Space Administration Special Publication-4027, 1997), p. 147.

[147] "Advanced X-Ray Astrophysics Facility Development," Office of Space Science and Applications Fiscal Year 1991 Estimates, Budget Summary, p. RD 3-13.

[148] "National Aeronautics and Space Administration Fiscal Year 1997 Estimates," p. SI-14.

[149] *Aeronautics and Space Report of the President, 1988 Activities* (Washington, DC: National Aeronautics and Space Administration, 1990), p. 2.

[150] "Smithsonian Astrophysical Observatory Wins AXAF Contract," *NASA News* Release 91-46, March 21, 1991.

[151] *Aeronautics and Space Report of the President, Fiscal Year 1992 Activities* (Washington, DC: National Aeronautics and Space Administration, 1993), p. 12.

[152] The X-Ray Spectrometer (XRS), originally planned for AXAF, became the prime instrument on the fifth Japanese x-ray astronomy satellite, ASTRO-E. Launched in 2000, ASTRO-E failed to reach orbit.

[153] "About the Chandra," *http://chandra.harvard.edu/launch/mission/axaf_mission3.html* (accessed September 28, 2005).

Completion of the first and largest of the AXAF's eight mirrors took place in August 1994. Built by Hughes Danbury Optical Systems, this mirror would form part of the high-resolution mirror assembly, the central optical component in the 10-meter (32.8-foot) telescope.[155] The 48-inch (122-centimeter)-diameter mirror was the largest ever made to collect x-rays in space. The mirror's imaging quality for high-energy x-rays was two times better than originally specified, resulting in significant scientific capability improvement.[156]

In January 1995, measuring and polishing of the eight critical x-ray reflecting mirrors, the most precise optics ever developed for imaging x-rays, were completed four months ahead of schedule at Hughes Danbury Optical Systems. Measurements indicated that the shape and smoothness exceeded program goals; they had an average smoothness of 3 angstroms, the width of just three atoms. Critical measurements were made using several techniques and pieces of equipment to eliminate the possibility of a flaw in the measuring equipment. The mirrors were then shipped to Eastman-Kodak for alignment and to the Optical Coating Laboratory, Inc., for iridium coating. The mirrors were returned to Kodak, integrated, and aligned into the High Resolution Mirror Assembly.[157] Assembly was completed between May and October 1996. By the end of March 1997, the mirrors had successfully completed initial testing at Marshall Space Flight Center's X-ray Calibration Facility. The test results showed that the telescope's focus, with a resolution 10 times greater than previous x-ray telescopes, was "very clear, very sharp."[158] After a second phase of successful testing of the observatory's science instruments, the mirrors were shipped in May to TRW, Inc. in California, where the telescope was assembled and tested (see figure 4–36).[159] Assembly was completed in March 1998. In April,

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[154] Warren E. Leary, "Satellite Will Offer X-ray View of the Cosmos," *New York Times*, (March 31, 1998: B9, B12, reprinted at *http://www.physics.ohio-state.edu/~wilkins/writing/Assign/topics/xray-telescope.html* (accessed September 28, 2005).

[155] In late 1989, Perkin-Elmer (the company that had manufactured the Hubble primary mirror and which had the AXAF development contract in the early 1980s) sold its optical division to Hughes Danbury Optical System, a subsidiary of Hughes Aircraft. Chaisson, *The Hubble Wars*, p. 150.

[156] "NASA Completes First Mirror for AXAF Observatory," *NASA News* Release: 94-139, August 24, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-139.txt* (accessed September 28, 2005).

[157] "NASA's X-ray Telescope Mirrors Completed Ahead of Schedule," *NASA News* Release 95-10, January 30, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-10.txt* (accessed September 28, 2005).

[158] "Advanced X-Ray Telescope Mirrors Provide Sharpest Focus Ever" Chandra Press Room, Release 97-48, March 20, 1997, *http://chandra.harvard.edu/press/97_releases/press_032097.html* and *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-048.txt* (accessed May 16, 2006).

[159] "Testing Shows X-Ray Telescope Mirrors Give Sharp Focus," *Marshall Star* 37 (March 26, 1997): 2, *http://marshallstar.msfc.nasa.gov/3-26-97.pdf* (accessed October 1, 2005). Also Joy Carter, "Mirrors Depart Center: AXAF Assembly Next," *Marshall Star* 37 (May 7, 1997): 1, *http://marshallstar.msfc.nasa.gov/5-07-97.pdf* (accessed October 1, 2005).

NASA announced a contest to select a new name for the observatory, and in December announced "Chandra" as the new name in honor of the late Indian-American Nobel Laureate Subrahmanyan Chandrasekhar. After delays to carry out additional testing at TRW, Inc. and to correct some problems, the Chandra was shipped to Kennedy Space Center on February 4, 1999.[160] The Chandra was launched on July 23, 1999.

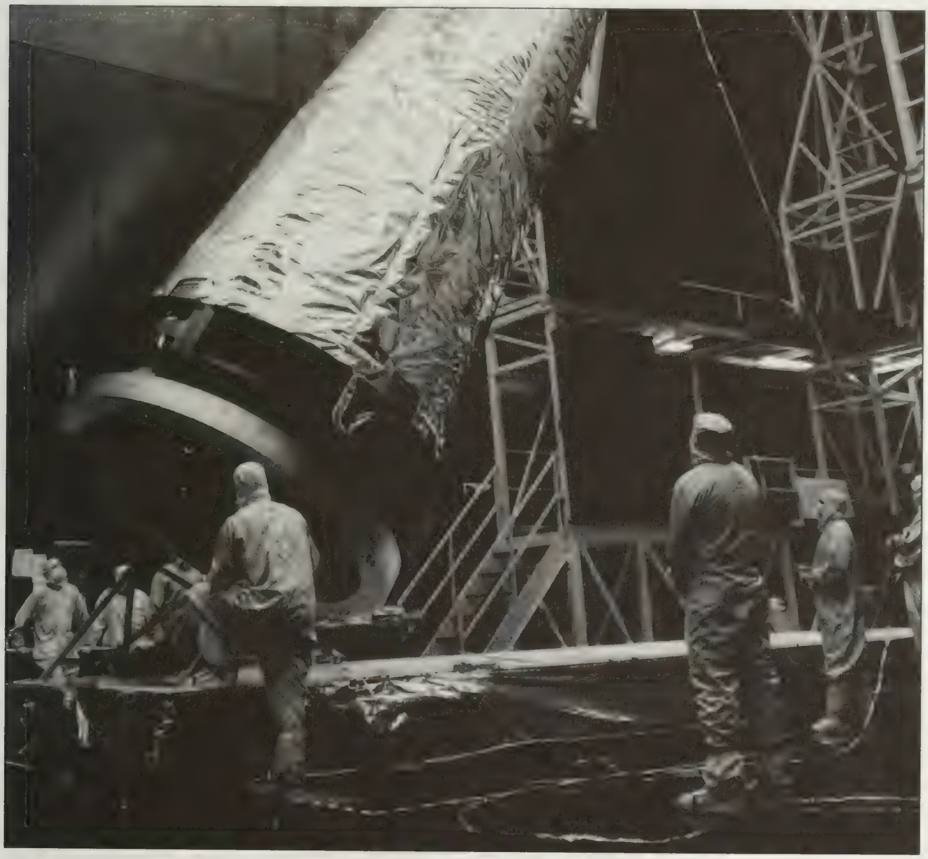

Figure 4–36. Chandra Optical Bench Assembly at TRW. (Northrop Grumman Space Technology)

Chandra Observatory

The Chandra X-Ray Observatory has three major assemblies: the spacecraft, telescope, and science instrument module (see Figure 4–37). The spacecraft module contains computers, communication antennae, and data recorders to transmit and receive information between the observatory and ground stations. The on-board computers and sensors—with ground-based control center assistance—command and control the observatory and monitor observatory health. The spacecraft module also provides rocket propulsion to move and aim the entire observatory. The module contains an aspect camera that tells the observatory its position and orientation relative to the stars and a Sun sensor that protects the module from excessive light. Two three-panel solar arrays provide the observatory with 2,350 watts of electrical power and charge three nickel-hydrogen batteries that supply backup power.

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[160] "Chandra X-Ray Observatory Arrives at KSC for Processing," *NASA News Release On-Line*, Kennedy Space Center Release no. 10-99, February 4, 1999, *http://www-pao.ksc.nasa.gov/kscpao/release/1999/10-99.htm* (accessed September 28, 2005).

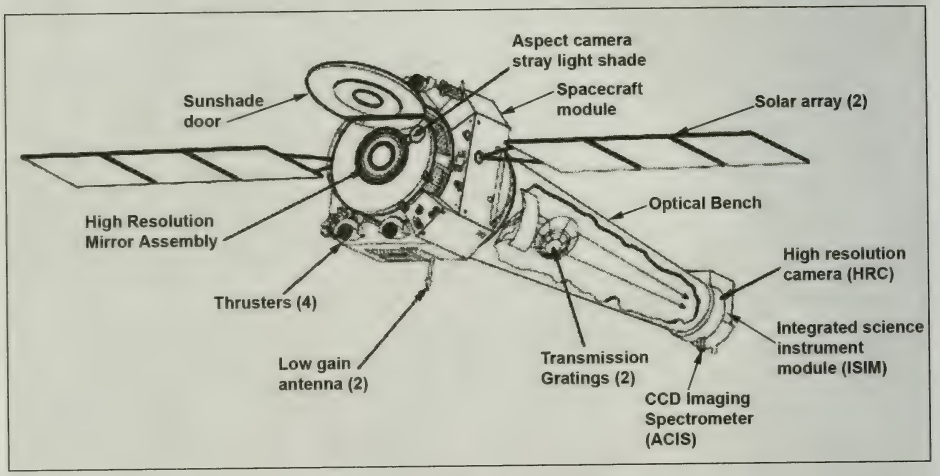
Aspect camera stray light shade
Sunshade door
Spacecraft module
Solar array (2)
Optical Bench
High Resolution Mirror Assembly
High resolution camera (HRC)
Thrusters (4)
Integrated science instrument module (ISIM)
Low gain antenna (2)
Transmission Gratings (2)
CCD Imaging Spectrometer (ACIS)

Figure 4–37. Chandra X-Ray Observatory.

The High-Resolution Mirror Assembly is the heart of the telescope system. Since high-energy x-rays would penetrate a normal mirror, special cylindrical mirrors were created. The two sets of four nested mirrors resemble tubes within tubes. Incoming x-rays graze off the highly polished mirror surfaces which focus the x-rays to a tiny spot, about half the width of a human hair, on the focal plane about 30 feet (9 meters) away. The focal plane science instruments, the Advanced Charged Couple Imaging Spectrometer (ACIS) and High Resolution Camera (HRC), capture sharp images formed by the mirrors and provide the following information about incoming x-rays: number, position, energy, and arrival time. The mirrors are the largest of their kind and the smoothest ever created. The largest of the eight mirrors is almost 4 feet (1.2 meters) in diameter and 3 feet (0.9 meter) long. Assembled, the mirror group weighs more than one ton (907 kilograms).

The mirror assembly is encased in the cylindrical telescope portion of the observatory. The entire length of the telescope is covered with reflective multilayer insulation that helps heating elements inside the unit keep a

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constant internal temperature. By maintaining a precise temperature, the mirrors within the telescope are not subject to expansion and contraction—thus ensuring greater observation accuracy.

The assembled mirrors were tested at Marshall Space Flight Center's X-Ray Calibration Facility. The calibration facility verified that the observatory could differentiate between objects separated by one-half arc second. With its combination of large mirror area, accurate alignment, and efficient x-ray detectors, the Chandra has eight times greater resolution and is 20 to 50 times more sensitive than any previous x-ray telescope.[161]

Two additional science instruments provide detailed information about the x-ray energy, the Low Energy Transmission Grating (LETG) and High Energy Transmission Grating (HETG) spectrometers. These grating arrays can be flipped into the path of the x-rays just behind the mirrors, where they redirect (diffract) the x-rays according to their energy. The HRC or ACIS measure x-ray position to determine the exact energy. The science instruments have complementary capabilities to record and analyze x-ray images of celestial objects and probe their physical conditions with unprecedented accuracy.

The focal plane instruments are mounted on the Science Instrument Module (SIM). The SIM contains mechanisms to move the science instruments in and out of the focal plane, insulation for thermal control, and electronics to control the operation of the science instruments through the spacecraft communication, command, and data management systems.

The science instruments are controlled by commands transmitted from the Operations Control Center in Cambridge, Massachusetts. A preplanned sequence of observations is uplinked to the Chandra and stored in the on-board computer for later execution.

Data collected with Chandra observations is stored on a recorder for later transmission to the ground every 8 hours during regularly scheduled DSN contacts. This data is transmitted to JPL and then to Operations Control at the Chandra X-ray Center (CXC) in Cambridge, Massachusetts, for processing and analysis by scientists.[162] Table 4–50 provides further mission details.

Space Infrared Telescope Facility

The SIRTF (renamed the Spitzer Space Telescope after its 2003 launch) was the fourth and final Great Observatory. It fills in a gap in wavelength coverage not available from the ground—the thermal infrared. The SIRTF was launched into space by a Delta rocket on August 25, 2003.

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[161] "The World's Most Powerful X-ray Telescope," STS-93 Press Kit, updated July 8, 1992, p. 21, *http://jsc.nasa.gov/history/shuttle_pk/pk/Flight_095_STS-093_Press_kit.pdf* (accessed September 28, 2005).

[162] "About Chandra: Science Instruments," *http://chandra.harvard.edu/about/science_instruments.html* (accessed September 28, 2005).

The SIRTF (which originally stood for the Shuttle Infrared Telescope Facility) was first proposed in 1979 in "A Strategy for Space Astronomy and Astrophysics for the 1980s" published by the National Research Council of the National Academy of Sciences. It was envisioned as an astrophysics facility to be developed for the Spacelab. In 1983, NASA issued an announcement of opportunity (AO) to build instruments and conduct observations with a large Shuttle-based telescope. At the time, the first flight was expected to occur around 1990, followed approximately a year later by a second flight.

The SIRTF AO coincided with launch of the international Infrared Astronomy Satellite (IRAS) in January 1983, the first infrared satellite mission. Due largely to its impressive early science returns, NASA amended the AO in September 1983 to include "the possibility of a long duration [free-flyer] SIRTF mission." The flight of a Shuttle-based infrared telescope in 1985 showing that the Shuttle vehicle released considerable contaminating infrared emissions helped NASA decide to proceed with a free-flying observatory. The name of the facility was changed to the Space Infrared Telescope Facility, to reflect its new design.[163]

In 1989, the National Research Council of the National Academy of Sciences commissioned the Astronomy and Astrophysics Survey Committee (AASC), consisting of members from the astronomy and astrophysics communities, to recommend the most significant ground- and space-based initiatives for the 1990s. The committee, which became known as the Bahcall Committee after its chairman, John Bahcall, released its 1991 report, *The Decade of Discovery in Astronomy and Astrophysics,* or the Bahcall Report. The report emphasized the importance of the 1-micron to 1,000-micron infrared and submillimeter portion of the electromagnetic spectrum for studying some of the most critical problems of astrophysics. The report also cited the advances made in infrared detector technology. It also recommended that the SIRTF be "the highest priority for a major new program in space-based astronomy" and the culmination of NASA's Great Observatory program. This telescope, the Executive Summary said, "would be almost a thousand times more sensitive than earth-based telescopes operating in the infrared."[164] The intent was to launch the facility early enough to allow the facility's science to overlap with the science produced by Hubble and AXAF. The report listed four research areas in which the SIRTF was expected to make scientific contributions: 1) formation of planets and stars; 2) the origin of energetic galaxies and quasars; 3) distribution of matter and galaxies; and 4) formation and evolution of galaxies.

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[163] "Early History," Spitzer Space Telescope, *http://www.spitzer.caltech.edu/about/earlyhist.shtml* (accessed April 26, 2006).

[164] National Research Council, Commission on Physical Sciences, Mathematics, and Applications, "Executive Summary" in *The Decade of Discovery in Astronomy and Astrophysics*, (Washington, DC: National Academy Press, 1991), *http://www.nap.edu/execsumm/0309043816.html* (accessed April 26, 2007). (Book available at *http://darwin.nap.edu/books/0309043816/html.*)

Soon after Bahcall Report publication, severe pressures on NASA's budget led to SIRTF, and other mission, redesign. The facility had two significant rescopings within five years, changing from a massive observatory with development costs exceeding $2.2 billion and a planned launch on a Titan launch vehicle to a more modest Delta-launched observatory costing approximately $400 million. Scientists and engineers redesigned the SIRTF with the goal of reducing the cost of every element—the telescope; instruments; spacecraft; ground system; mission operations; and project management. The SIRTF Science Working Group identified a handful of the most compelling problems in modern astrophysics where the SIRTF could make the greatest contributions. The SIRTF's primary scientific areas of focus were the following: protoplanetary and planetary debris disks; brown dwarfs and super planets; ultraluminous galaxies and active galactic nuclei; and the early universe–deep surveys.[165] An important feature of SIRTF redesign was to abandon the idea of placing the observatory into Earth orbit and, instead, insert the facility into an Earth-trailing heliocentric orbit, an orbit where the facility would drift behind Earth while it circles the Sun.[166]

Following the SIRTF's last redesign in 1994, the Committee on Astronomy and Astrophysics, a joint activity of the National Research Council's Space Studies Board and the Board on Physics and Astronomy, established a SIRTF Task Group. NASA asked the group to assess the scientific capabilities of the redesigned facility. The Task Group concluded in its report sent to NASA in April 1994 that the facility's science capabilities remained "unparalleled" in its potential for addressing the areas discussed in the Bahcall Report and still "merits the high-priority ranking it received in the Bahcall Report."[167]

In June 1996, NASA awarded three contracts for facility development. Lockheed-Martin Missiles and Space and Ball Aerospace & Technologies Corporation were chosen to team with JPL to design, develop, test, and integrate the SIRTF. JPL managed the SIRTF project for NASA.[168]

On March 25, 1998, NASA Administrator Goldin authorized the start of work on the SIRTF, signaling the start of the facility design and development phase. The SIRTF was then scheduled for launch in December 2001. The design and development cost cap was $458 million. To add to Lockheed Martin's and Ball Aerospace's responsibility for mission elements, the SAO, Cornell University, and the University of Arizona were providing the three science instruments. The SIRTF Science Center at the California Institute of Technology would receive and process JPL data and work with the astronomy community.[169]

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[165] Office of Space Science, Science Aeronautics and Technology "FY 1998 Estimates, Budget Summary," pp. SAT 1-19–SAT 1-20.

[166] "Innovations: Clever Choice of Orbit," Spitzer Space Telescope, *http://www.spitzer.caltech.edu/about/orbit.shtml* (accessed April 26, 2006).

[167] "Report of the Task Group on SIRTF [Spitzer] & SOFIA," Sent to NASA April 21, 1994, *http://www.spitzer.caltech.edu/about/tgss.shtml* (accessed April 26, 2007).

[168] "Contracts Awarded for Space Infrared Telescope Facility," Jet Propulsion Laboratory, June 24, 1996, *http://www.jpl.nasa.gov/releases/96/sirtfcon.html* (accessed April 26, 2007).

Ulysses

Ulysses was the first mission to study the environment of space above and below the Sun's poles and the first mission to give scientists a look at the variable effect of the Sun on the space surrounding it.[170] The primary goal of Ulysses was to characterize the heliosphere as a function of solar latitude, specifically the relationship between the Sun and its magnetic field and particle emissions (solar wind and cosmic rays), affording a better understanding of the effect of solar activity on Earth's weather and climate.

Ulysses was based on a proposed project in the late 1950s called "Out of Ecliptic," which was to have been a two-spacecraft operation with one spacecraft furnished by the United States and the second furnished by the ESA. Between 1977 and 1979, the project name was changed to the International Solar Polar Mission (ISPM). In 1979, NASA and the ESA signed a memorandum of understanding for the mission. Delays in Shuttle development and concerns over the effectiveness of the inertial upper stage led the U.S. House Appropriations Committee to recommend in the 1980 Supplemental Appropriations Bill that the mission be terminated. In 1981, budget cuts led NASA to cancel the U.S. spacecraft contribution to the mission, which was restructured to a single ESA spacecraft mission. It was the first time NASA had withdrawn from an international agreement. The cancellation caused such an uproar that the United States agreed to furnish transportation for the ESA spacecraft.[171] In 1984, the mission was renamed the Ulysses project.

In its final configuration, the ESA provided the spacecraft, which was built by Dornier Systems, Germany, and managed the mission operations. NASA provided the Space Shuttle and the inertial upper stage and payload assist module to put Ulysses in its correct out-of-ecliptic orbit. The U.S. Department of Energy supplied the radioisotope thermoelectric generator that powered the spacecraft. Teams from universities and research institutes in Europe and the United States provided the 11 science instruments.

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[169] "NASA Starts Work on New Space Infrared Telescope Facility," Jet Propulsion Laboratory, March 25, 1998, *http://www.jpl.nasa.gov/releases/98/sirtfgo.html* (accessed April 26, 2006).

[170] "Ulysses Factsheet," ESA Space Science, *http://www.esa.int/esaSC/SEMUBG1A6BD_index_0.html* (accessed September 22, 2005).

[171] John Naugle, comments on chapter 4, Space Science, of *NASA Historical Data Book, 1989–1998*. Also "Ulysses Mission Operation Report," Office of Space Science and Applications, Report no. S-448-41-90-01, p. 1. (NASA History Office Electronic Document, Record no. 30797).

Ulysses was scheduled to launch in 1986, but it was another victim of the *Challenger* accident and elimination of the Centaur upper stage. The launch took place in October 1990 using the Shuttle and both an inertial upper stage and a payload assist module.

After launch, a combination of solid-fuel motors propelled Ulysses toward Jupiter. Ulysses arrived at Jupiter on February 8, 1992, to begin the gravity-assist maneuver that bent the spacecraft's flight path downward and away from the ecliptic plane. This put the spacecraft into its unique solar orbit. Ulysses passed over the Sun's south pole in 1994 and the north pole in 1995, and the spacecraft began its second complete orbit of the Sun in 1998.[172] Although scientific observations at Jupiter on the way to the Sun were not a primary objective, scientists used the opportunity to study Jupiter's magnetosphere. The results exceeded all expectations. The spacecraft's path took it to areas where earlier spacecraft (Pioneer 10, Pioneer 11, Voyager 1, and Voyager 2) had not flown, and its instruments produced a wealth of new information relating to the Jovian magnetosphere.

The events of greatest scientific interest occurred when Ulysses was at or higher than 70 degrees latitude at both the Sun's south and north poles. The phenomena being studied were strongly influenced by the 11-year solar cycle.

During Ulysses' primary mission, which covered half of the solar cycle, the spacecraft passed over the Sun's southern pole and then flew northward until it passed over the Sun's northern pole, surveying both polar regions for the first time (see Figure 4–38). On June 26, 1994, Ulysses reached 70° S, where the spacecraft began four months of high-latitude observations of the complex forces in the Sun's corona. Ulysses passed over the solar south pole at a distance of 350 million kilometers (217 million miles) on September 13, 1994, and it passed over the solar north pole at a distance of 140 million kilometers (87 million miles) on July 31, 1995, at its maximum latitude of 80.2° north of the Sun's equator.[173] When the spacecraft reached the summit of its trajectory over the Sun, Ulysses had traveled about 1.86 billion miles (3 billion kilometers).[174] Scientists learned that the Sun has a uniform magnetic field over the poles and lacks the theoretical "cosmic-ray funnel" thought to allow easy access of cosmic rays into the polar regions. Data also revealed that the gas in the heliosphere consists principally of energetic atoms from which one or more electrons has been removed to form ions. These ions become positively charged when they lose their electrons. In addition, three classes of charged particles were identified from their energy and place of origin. Scientists also found that the space between the Sun's equator and poles could be divided into distinct regions, just as Earth could be divided into tropical, temperate, and arctic zones.

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[172] "Ulysses Solar Polar Mission," *http://www.nasa.gov/centers/jpl/missions/ulysses.html* (accessed August 25, 2005).

[173] "Solar and Deep Space Probe Programs and Primary Mission Achievements, Japanese Aerospace Exploration Agency, *http://spaceinfo.jaxa.jp/note/tansa/e/tan9907_satwrld05_e.html* (accessed August 15, 2005).

[174] "Ulysses Climbs to Highest Latitude over Sun's Northern Pole," July 1995, *http://ulysses.jpl.nasa.gov/pdfs/highestnlatjul95.pdf* (accessed April 28, 2006).

The primary mission ended on September 29, 1995, when the spacecraft completed the northern polar pass. Ulysses then began traveling back to Jupiter's orbit, the farthest point from the Sun, reaching the planet on April 17, 1998. Ulysses began its second solar orbit and, as it started looping back toward the Sun, revisited the Sun's south pole in 2000 and north pole in 2001.[175] Aboard Ulysses. SWICS measurements reported in May 1996 found that helium-3, a lighter isotope of the element, had increased a "surprisingly small" amount since universe formation, allowing a more precise estimate of the amount of dark matter in the universe. Scientists believed that as much as 90 percent of the universe consisted of dark matter.[176] During March and April of 1997, scientists had the opportunity to use the Ulysses spacecraft's unique, high-latitude orbit to gain understanding of changes in comet Hale-Bopp as it neared the lower latitudes of the Sun while spewing its outer layers of gas and dust. The Ulysses Comet Watch group, a collaboration between JPL and the University of Colorado, provided worldwide observations of the returning comet as it descended from the polar regions of the Sun. The Ulysses group watched for changes in the comet's narrower, paler plasma tail, which consisted of ionized gas emitted by the comet and picked up by the magnetic field being swept along by the solar wind.[177] According to observations, the plasma tail of the comet was found to be surprisingly structureless at high latitude, and a tail disconnection was observed on May 7–May 8, 1997.[178]

The capture of a gamma-ray flare from a magnetic star was a highlight of 1998. On August 27, 1998, Ulysses and other spacecraft with high-energy radiation detectors in space observed a gamma-ray burst located in the constellation Aquila (20,000 light years away). Only Ulysses measured the magnitude of the event, which was twice that of any other recorded burst. The star, SGR1900+14, was a "magnetar" (for magnetic star), a class of objects with the strongest magnetic fields known in the universe. SGR1900+14 was thought to have a magnetic field about a thousand trillion times stronger than Earth's magnetic field and about one thousand times stronger than any found elsewhere in the universe.[179] This secondary phase lasted until December 2001. Table 4–51 lists mission milestones.

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[175] Diane Ainsworth, "Ulysses Completes First Full Orbit Around the Sun," *Universe*, Jet Propulsion Laboratory, 28 (May 1, 1998): 1 (NASA History Office Folder 33866). Also Diane Ainsworth, "Ulysses Finds Surprises During First Solar Orbit," *Universe*, Jet Propulsion Laboratory, 26 (January 12, 1996): 5; "Ulysses Factsheet," ESA, *http://www.esa.int/esaSC/SEMUBG1A6BD_index_0.html* (accessed September 22, 2005).

[176] "Ulysses Measurements Give New Clues to Dark Matter," Jet Propulsion Laboratory, May 16, 1996, *http://ulysses.jpl.nasa.gov/pdfs/heliummay96.pdf* (accessed April 28, 2006).

[177] "Ulysses Scientists Begin Capturing Unique View of Hale-Bopp," Jet Propulsion Laboratory, March 1997, *http://ulysses.jpl.nasa.gov/news/comet_studies.html* (accessed April 28, 2006).

[178] "Ulysses Scientific Results: Fall 1997," *http://ulysses.jpl.nasa.gov/pdfs/results-97.pdf* (accessed April 28, 2006).

[179] "Ulysses Captures Gamma-Ray Flare from Shattered Star," Jet Propulsion Laboratory, October 1, 1998, *http://ulysses.jpl.nasa.gov/pdfs/ulygamburstoct98.pdf* and "Ulysses Captures Gamma-Ray Flare from Magnetic Star," *http://ulysses.jpl.nasa.gov/pdfs/ulss98-12.pdf* (accessed April 28, 2006).

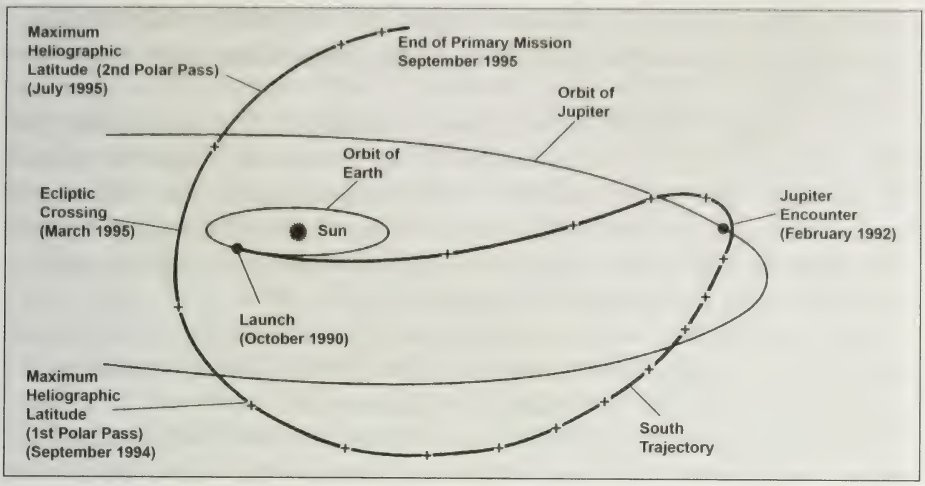
Maximum
Heliographic
Latitude (2nd Polar Pass)
(July 1995)
End of Primary Mission
September 1995
Orbit of
Jupiter
Orbit of
Earth
Ecliptic
Crossing
(March 1995)
Sun
Jupiter
Encounter
(February 1992)
Launch
(October 1990)
Maximum
Heliographic
Latitude
(1st Polar Pass)
(September 1994)
South
Trajectory

Figure 4–38. Ulysses Primary Mission.

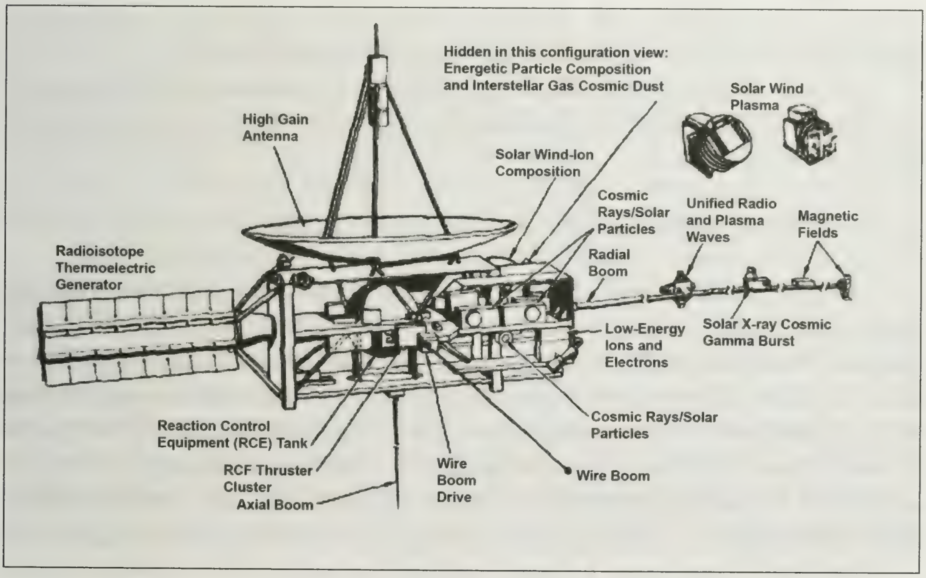
Hidden in this configuration view:
Energetic Particle Composition
and Interstellar Gas Cosmic Dust
High Gain
Antenna
Solar Wind
Plasma
Solar Wind-Ion
Composition
Cosmic
Rays/Solar
Particles
Unified Radio
and Plasma
Waves
Magnetic
Fields
Radioisotope
Thermoelectric
Generator
Radial
Boom
Low-Energy
Ions and
Electrons
Solar X-ray Cosmic
Gamma Burst
Cosmic Rays/Solar
Particles
Reaction Control
Equipment (RCE) Tank
RCF Thruster
Cluster
Axial Boom
Wire
Boom
Drive
Wire Boom

Figure 4–39. Ulysses Configuration.

The spacecraft's systems and scientific instruments were contained within a main spacecraft bus (see Figure 4–39). Ulysses maintained communication with Earth via a parabolic high-gain antenna. After release from *Discovery*'s cargo bay, the spacecraft deployed a radial boom carrying several experiment sensors as well as a dipole wire boom and an axial boom, which served as antennae for a radio-wave/plasma-wave experiment.

The spacecraft's main computer was the on-board data handling system, responsible for processing commands received from the ground as well as managing and passing on all data from each Ulysses science instrument. Each of the system's two tape recorders could store 45.8 million bits of data—representing 16 hours to 64 hours of data-taking, depending on how often data was sampled.

The attitude control system was responsible for determining the spacecraft's attitude in space, as well as firing thrusters to control the attitude and spin rate. This system included a redundant computer, Sun sensors, and the reaction control system with eight thrusters and the hydrazine fuel system. The load of monopropellant hydrazine fuel was stored in a single diaphragm tank mounted on the spacecraft's spin axis.

The spacecraft's telecommunications system included two S-band receivers; two 5-watt S-band transmitters; two 20-watt X-band transmitters; a high-gain antenna; and two smaller low-gain antennae.

Ulysses was powered by an RTG similar to RTGs flown on previous solar system exploration missions. RTGs are required for these deep-space missions because solar arrays large enough to generate sufficient power at long distances from the Sun would be too large and heavy to be launched by available launch vehicles. In the RTG, heat produced by the natural decay of plutonium-238 is converted into electricity by thermocouples.[180]

Ulysses' scientific payload consisted of nine instruments (see Table 4–52). To add, the spacecraft radio was used to conduct a pair of experiments and communicate with Earth.

Advanced Satellite for Cosmology and Astrophysics (Astro-D)

The ASCA (originally Astro-D) was a Japanese-led program involving the United States as a participating partner. Astro-D was renamed ASCA after launch. The Japanese characters for ASCA literally mean "flying bird"; it was also the name of an ancient era of Japan when the country was modernized and culture flourished. In return for its scientific instrument contributions, the United States received 15 percent of the observing time and shared an additional 25 percent observing time for collaborative U.S.-Japan scientific investigations.[181]

The ASCA was Japan's fourth cosmic x-ray astronomy mission and the second for which the United States provided part of the scientific payload. The Japanese Institute of Space and Astronautical Science (ISAS) provided overall program management, the launch vehicle, the spacecraft, and two gas scintillation imaging system detectors. NASA provided four tested, thin-foil, grazing-incidence telescope mirrors and two x-ray CCD solid state detectors. NASA also provided telemetry tracking support using DSN ground stations.

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[180] "STS-41 Press Kit," p. 13.

[181] "ASTRO-D Mission Operation Report," Report no. S-689-93-01, cover memo (NASA History Office Folder 5670).

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The ASCA was the first "high energy imaging and spectroscopy" mission to cover a wide energy range exceeding 10 keV and the first to combine imaging capability with a broad passband, good spectral resolution, and a large effective area.[182] The mission also was the first satellite to use CCDs for x-ray astronomy. The primary scientific purpose of the ASCA was the x-ray spectroscopy of astrophysical plasmas—especially the analysis of discrete features such as emission lines and absorption edges.[183]

The ASCA was launched on February 20, 1993. After approximately eight months of on-orbit calibration and performance verification, and due to the proprietary data rights to which the mission developers were entitled, the mission changed to a general/guest observer status for the remainder of the mission. In this phase, the proprietary data was archived with the remainder of the data, and the observing program opened to astronomers based at Japanese and U.S. institutions as well as those located in ESA member states.[184]

The ASCA carried four large-area identical XRTs. At the focus of two of the telescopes were Gas Imaging Spectrometers (GISs). At the focus of the other two XRTs were Solid-state Imaging Spectrometers (SISs). The sensitivity of the ASCA's instruments allowed the first detailed, broadband spectra of distant quasars to be derived. In addition, the ASCA's suite of instruments provided the best opportunity to date for identifying the sources whose combined emission made up the cosmic x-ray background.[185] Data from the x-ray detectors were processed by the on-board data processing unit and telemetered in real-time and stored in the on-board data recorder.

The spacecraft was three-axis stabilized, and its pointing accuracy was approximately 30 arc seconds, with stability better than 10 arc seconds. The attitude control system consisted of a four-gyroscope (plus one back-up gyroscope) inertial reference system; four reaction wheels; two star trackers; three magnetic torquers for unloading angular momentum; and the control electronics. The spacecraft orientation was limited to direct the solar paddles within 30 degrees from the Sun. This orientation limited the observable sky to a belt within which the Sun angle was between 60 degrees and 120 degrees. The spacecraft was given a bias angular momentum that always was directed to the Sun if an abnormality in the attitude control occurred. This bias angular momentum could secure enough power when the spacecraft went automatically into a safe-hold mode (spinning around the Sun vector).

The ISAS managed ASCA operations, which were conducted mainly by Japanese scientists and graduate students from various groups. Among other duties, several scientists were in charge of scheduling observations, programming, and executing commands; tracking and quick look; monitoring the health of the spacecraft and instruments; and first-order processing of the data. During the satellite's 15 daily orbits, direct contact was made five times each day from the ISAS Kagoshima Station and five to eight times each day from NASA's DSN stations at Goldstone, California; Madrid, Spain; and Canberra, Australia. Each satellite contact lasted about 10 minutes.[186] Table 4–53 provides further mission details.

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[182] "ASTRO-D Mission Operation Report," Report no. S-689-93-01, p. 6 (NASA History Office Folder 5670).

[183] "The ASCA Mission (1993–present)," (NASA History Office Folder 5670).

[184] "The Advanced Satellite for Cosmology and Astrophysics (ASCA)," *http://heasarc.nasa.gov/docs/asca/asca2.html* (accessed August 28, 2005).

[185] "The Advanced Satellite for Cosmology and Astrophysics (ASCA)," *http://legacy.gsfc.nasa.gov/docs/asca/asca2.html* (accessed August 29, 2005).

BeppoSAX

BeppoSAX was an x-ray astronomy satellite named "Beppo" in honor of Italian physicist Giuseppe Occhialini, a pioneer in gamma ray and cosmic ray astronomy.[187] Launched from Cape Canaveral, Florida, in April 1996 on the 100th Atlas-Centaur launch, it was a project of the Italian Space Agency with participation by the Netherlands Agency for Aerospace Programs. It was the first x-ray mission with a scientific payload covering more than three decades of energy—from 0.1 keV to 300 keV—with a relatively large effective area, medium energy resolution, and imaging capabilities in the range from 0.1 keV to 10 keV.

A consortium of institutes in Italy and the Netherlands and the ESA's Space Science Department supported development of the spacecraft. The Max Planck Institut für extraterrestrische Physik (Max Planck Institute for Extraterrestrial Physics) also collaborated for x-ray mirror testing and calibration of the concentrator/spectrometer system. The BeppoSAX U.S. Coordination Facility was established at NASA's High Energy Astrophysics Science Archive Research Center in February 1997. The facility's aim was to provide a BeppoSAX archive in the United States. The facility worked closely with the BeppoSAX Science Data Center in Rome, Italy. In addition, the facility provided basic support to the U.S. astronomical community for proposal preparation and use of satellite data.

With more precision than ever before achieved, BeppoSAX could determine the position of gamma-ray bursts at x-ray wavelengths and relay that information to astronomers. Astronomers could then investigate these short-lived bursts using powerful, ground-based optical telescopes and the orbiting Hubble Space Telescope. BeppoSAX, working in tandem with the CGRO and RXTE, offered the possibility of expanding the number of gamma-ray burst detections.[188] See Table 4–54 for further mission details.

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[186] "Mission Overview," ASCA Guest Observer Facility, *http://agile.gsfc.nasa.gov/docs/asca/newsletters/mission_overview1.html* (accessed August 29, 2005).

[187] "Beppo" is a nickname for Giuseppe. Giuseppe Occhialini was a member of at least two teams in which the team leader received a Nobel Prize. He also was instrumental in forming the European Space Research Organization, predecessor to the ESA.

[188] "Gamma-Ray Bursts Solved," CGRO Science Support Center, *http://cossc.gsfc.nasa.gov/docs/cgro/epo/news/opcounter.html* (accessed September 1, 2005).

New Millennium Program

The New Millennium Program was an aggressive technology development and demonstration program designed to bring about a revolution in the design, development, and implementation of science spacecraft and instruments. The program was a partnership between NASA's OSS and the Office of Space Access and Technology (OSAT) working closely with the science community. The program encompassed spacecraft components and subsystems; science instruments; and streamlined design, development, and qualification methodologies. The OSS[189] funded the program, and JPL managed program implementation.[190]

The New Millennium Program was established in response to the need for low-mass, affordable spacecraft and instruments, as well as the need lower development, launch service, and mission operations costs due to shrinking budgets. The program's idea was to try out new technologies on inexpensive spacecraft in preparation for more complex future missions. Established in 1995, the program formed partnerships among NASA's space science and Earth science organizations and organizations in government, private industry, academia, and the nonprofit sector, enabling the expertise and know-how of scientists, engineers, and managers to be pooled and used as a resource to meet program goals.[191] The primary program objectives were to increase the performance capabilities of spacecraft and instruments while simultaneously reducing total costs of future science missions, thereby increasing the science mission flight rate. Key areas addressed included reducing spacecraft and instrument launch volume and weight, which allowed smaller launch vehicles to be used, and increasing overall spacecraft autonomy and performance to reduce operations costs and increase science return.

Although the objective of the New Millennium Program technology validation missions was to enable future science missions, the New Millennium Program missions were not science-driven. The missions were technology-driven with the principal requirements coming from the needs of the advanced technologies forming the payload. The missions were high risk because they incorporated unproven technologies without, in most cases, functionally equivalent backups. The New Millennium Program tested and validated new technologies in a series of deep space and Earth-orbiting missions. One New Millennium Program mission flew during the decade ending in 1998, Deep Space 1. The launch vehicle also carried a secondary payload, the SEDSAT-1. See Table 4–55 for further mission details.

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[189] "New Millennium Program," Science, Aeronautics, and Technology Fiscal Year 1997 Estimates Budget Summary, p. SAT 1.1-40.

[190] "New Millennium Spacecraft," NASA Budget Fiscal Year 1996 Estimate, Science, Aeronautics, and Technology, Office of Space Science, Planetary Exploration, *http://www.hq.nasa.gov/office/budget/fy96/table.html* (accessed August 1, 2005).

[191] "New Millennium Program," *http://nmp.jpl.nasa.gov/PROGRAM/program-index.html* (accessed August 1, 2005).

Deep Space 1

Deep Space 1, a technology demonstrator funded by NASA's OSS, was the first launch of NASA's New Millennium Program and the program's first deep-space mission. Deep Space 1 was one of NASA's first deep-space launches where technology, rather than science, was the key focus.

Technologies tested on this mission included the following: a xenon ion engine; a solar concentrator array; autonomous navigation plus two other autonomy experiments; a small transponder; a Ka-band solid state power amplifier; and experiments in low-power electronics, power switching, and multifunctional structures (in which electronics, cabling, and thermal control were integrated into a load bearing element).[192]

Deep Space 1 probe construction began in 1995 after NASA chose JPL to design and build a spacecraft to flight-test cutting-edge technology systems that NASA wanted to test for future space missions. The 1,072-pound (486-kilogram) probe was designed and built in three years. Originally scheduled to launch in July 1998, late delivery of the spacecraft's power electronics system and an ambitious flight software development schedule (which together left insufficient time to test the spacecraft thoroughly for a July launch) delayed the launch until October 24. The new launch trajectory included a flyby of near-Earth asteroid 1992 KD.[193]

In space, all 12 technologies worked so well that NASA extended the probe's mission to fly toward a comet in July 1999. After validating all the technology, the primary Deep Space 1 mission successfully concluded in September 1999. The Deep Space 1 mission was the first mission to use the Delta II 7326 Med-Lite launch vehicle.[194]

Although there were 12 advanced technologies on Deep Space 1, the rest of the spacecraft was composed of current, less costly components that had been tested and used on other missions. This approach allowed the New Millennium Program to focus on proving that the program's advanced technologies worked in space, not on building complete spacecraft like those to fly on future missions. The octagonal, aluminum spacecraft structure was based on the three Miniature Seeker Technology Integration (MSTI) spacecraft built by Spectrum Astro, Inc. for the Ballistic Missile Defense Organization. Most of the components were mounted on the exterior of the bus, simplifying accessibility for replacement during integration and test.[195] Batteries and two solar panel wings attached to the sides of the frame powered the spacecraft. The solar

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[192] "Deep Space 1," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-061A* (accessed August 18, 2005).

[193] "New Deep Space 1 Trajectory Includes Asteroid Flyby," Jet Propulsion Laboratory Release, June 5, 1998, *http://stardust.jpl.nasa.gov/news/news22.html* (accessed August 17, 2005).

[194] "NASA's First New Millennium Mission: Deep Space 1," *www.spacetoday.org/SolSys/Comets/DeepSpace1.html* (accessed August 17, 2005).

[195] "Deep Space 1–General Interest: Spacecraft," *http://nmp.jpl.nasa.gov/ds1/gen/spacecraft.html* (accessed August 17, 2005).

panel, Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET II), was one of the technologies tested. The array used 720 lenses to focus sunlight onto 3,600 solar cells, each converting the light into electricity to power the ion propulsion system and the rest of the spacecraft. The solar array consisted of four 160-centimter by 113-centimeter (63-inch by 45-inch) panels. The array furnished 2,500 watts of power at 100 volts at the beginning of the mission; it furnished less power as the spacecraft moved farther from the Sun and the solar cells aged.[196] Communications were via a high-gain antenna, three low-gain antennae, and a Ka-band antenna, all mounted atop the spacecraft except for one low-gain antenna mounted on the bottom.

A xenon ion engine mounted in the propulsion unit on the bottom of the frame provided propulsion (see Figure 4–40). The 30-centimeter-diameter engine consisted of an ionization chamber into which xenon gas was injected. Electrons were emitted by a cathode traverse discharge tube and collided with the xenon gas, stripping off electrons and creating positive ions. The ions were accelerated through a 1,280-volt grid at 31.5 kilometers per second (19.6 miles per second) and ejected from the spacecraft as an ion beam, producing 0.09 newton of thrust at maximum power (2,300 watts) and 0.02 newton at the minimum operational power of 500 watts. The excess electrons were collected and injected into the ion beam to neutralize the electric charge. Approximately 17 kilograms (37 pounds) of the original 81.5 kilograms (180 pounds) of xenon were consumed during the primary mission.[197]

Students for the Exploration and Development of Space Satellite

The SEDSAT-1 was the secondary payload on the June 24, 1998, Delta 2 launch of Deep Space 1. Students at the University of Alabama, Huntsville, designed the microsatellite, which was placed into a 547-kilomter by 1,079-kilometer (340-mile by 670-mile) orbit inclined at 31.5 degrees. The spacecraft carried cameras to make images available over the World Wide Web and two radio amateur packet communications payloads. The on-orbit goals were the following:

- Provide multispectral remote sensing to the broadest possible community. The cameras were to collect in narrow wavebands chosen to coordinate with ground-based observations across the United States. Unlike other remote sensing systems, the data would be broadly accessible because it would be entirely in the public domain, and its communication system would be integrated into the World Wide Web.

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[196] "Solar Concentrator Arrays," Deep Space 1: Advanced Technologies, *http://nmp.jpl.nasa.gov/ds1/tech/scarlet.html* (accessed October 10, 2005).

[197] "Deep Space 1," NSSDC Master Catalog: Spacecraft *http://nssdc.nasa.gov/database/MasterCatalog?sc=1998-061A* (accessed August 18, 2005).

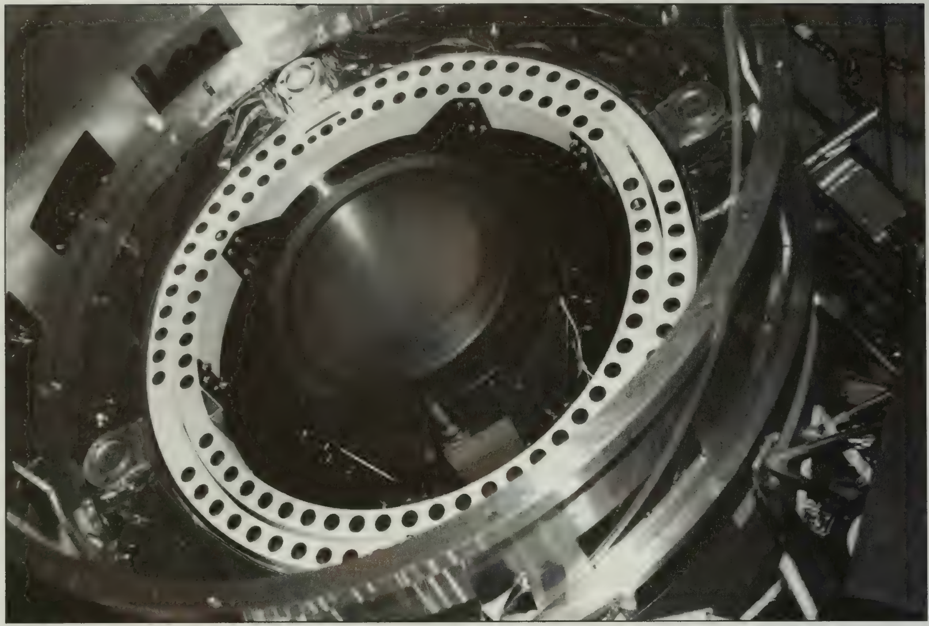

Figure 4–40. Deep Space 1 is lifted from its work platform, giving a close-up view of the experimental solar-powered ion propulsion engine. The ion propulsion engine was the first non-chemical propulsion to be used as the primary means of propelling a spacecraft. (NASA Photo No. KSC-98PC-1192)

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- Serve as a development platform for advanced microsatellite position determination and control algorithms. The satellite was to demonstrate a unique attitude determination system and new technology in active microsatellite control.
- Provide the amateur radio community with digital packet store-and-forward and analog repeater systems.
- Generate new data on the space performance of nickel-metal hydride batteries and advanced electronic components.
- Provide additional opportunities for space studies because of its on-board GPS, extensive reprogrammability, and other flexible instruments. The students developed an experiment to demonstrate mobile IP (Internet Protocol) on the SEDSAT that was to allow the SEDSAT to appear as an active node on the Internet.[198]

The satellite was launched with a known negative power configuration and suffered a failed uplink capability on October 27, 1988, which compromised full success. As a result, the spacecraft operated for more than two years transmitting only engineering health telemetry until the batteries were fully discharged. The reboot logic included a "non-transmit" period, allowing it to charge the batteries before it began transmitting again in a new cycle.[199] The SEDSAT was operational only in transmit mode at least until September 2003.[200]

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[198] "Sedsat Project Information," *http://www.seds.org/sedsat/info* (accessed October 10, 2005).

High Energy Transient Experiment/Satelite de Aplicaciones Cientificas-B

The Argentinean SAC-B and the HETE were launched together on a Pegasus XL launch vehicle on November 4, 1996 from NASA's facility at Wallops Island, Virginia. Goddard Space Flight Center provided one instrument on the SAC-B, the Hard X-Ray Spectrometer. Although the Pegasus achieved a nominal orbit, it did not eject the two spacecraft from the rocket as planned. Telemetry indicated a power failure on the transient power bus of the Pegasus third stage, causing three crucial pyrotechnics to fail to ignite. Thus, the system flew with the SAC-B, the HETE, and the Pegasus third stage connected together as a single 650-kilogram (1,433-lb) object. The HETE remained enclosed in the dual payload attachment fitting.

The SAC-B deployed its solar panels successfully and operated for about 10 hours. On-board software was modified to permit operation without a separation indication, and the attitude control system (ACS) was placed in safe-hold mode in an attempt to gain control and point the solar panels toward the Sun. However, the ACS was not designed to control such a massive tumbling object. With the Pegasus third stage shadowing at least part of the solar array, there was insufficient power to charge the batteries, even during the daylight part of the orbit. The SAC-B battery power continued to decrease, and subsequent passes over Wallops Island, Virginia, did not produce any signal from the satellite.

At the same time, on the morning of November 5, operators of a 23-meter (75-foot) very high frequency antenna at Wallops Island received a transmission while monitoring a frequency used by the HETE's emergency beacon. Subsequent passes over Los Alamos National Laboratory and Wallops Island also picked up a similar, though much weaker, signal. Unable to deploy solar panels to charge its batteries, the HETE expired several days after launch.[201] Because of the importance of gamma-ray burst science, NASA agreed to a second attempt using spare flight hardware from the HETE-1. In July 1997, the NASA funded the HETE-2, and construction began in mid-1997 at MIT.[202] HETE-2 was successfully launched on October 9, 2000.

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[199] "Sedsat," The Satellite Encyclopedia, *http://www.tbs-satellite.com/tse/online/sat_sedsat.html* (accessed October 10, 2005). Also Chris Lewicki, e-mail to author, October 12, 2005.

[200] Dennis Wingo, e-mail to author, October 12, 2005.

[201] "SAC-B," Quicklook, *http://msl.jpl.nasa.gov/QuickLooks/sacbQL.html*. Also "HETE," Quicklook," *http://msl.jpl.nasa.gov/QuickLooks/heteQL.html* (accessed August 11, 2005).

[202] "HETE-2 Spacecraft To Study Gamma Ray Bursts Fully Operational On-Orbit," Press Release AeroAstro, *http://www.aeroastro.com/releases/2000/pr_10_09_00.php* (accessed August 19, 2005).

The HETE-1 was to have been an international mission led by MIT. Its prime objective was to carry out the first multi-wavelength study of gamma-ray bursts with UV, x-ray, and gamma-ray instruments. A unique feature of the mission was its capability to localize bursts with several arc-second accuracy in near real-time aboard the spacecraft. These positions would be transmitted to the ground and picked up by a global network of primary and secondary ground stations, enabling sensitive follow-up studies. The HETE was Sun-pointing with four solar panels connected to the bottom of the spacecraft bus. Magnetic torque coils and a momentum wheel were to control spacecraft attitude.

The SAC-B was a small satellite built by the Argentinean National Commission of Space Activities. The SAC-B was designed to advance the study of solar physics and astrophysics through the examination of solar flares, gamma-ray bursts, diffuse x-ray cosmic background, and energetic neutral atoms. The satellite also was designed to test and characterize the performance of new equipment and technologies that might be used in future operational or scientific missions. The SAC-B was three-axis-stabilized, using two momentum wheels in a "V" configuration for roll and yaw control. Pitch axis control and momentum unloading were accomplished using magnetic torque coils. Coarse and fine Sun sensors, combined with magnetometer readings were to provide spacecraft attitude knowledge. See Table 4–56 for further details.

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International Solar-Terrestrial Physics Program

The ISTP program was an international, multi-spacecraft, collaborative science mission comprising a complement of satellites, ground-based observations, and theoretical investigations studying the Sun and Earth system in a global context. Goddard Space Flight Center managed the ISTP program, and NASA, the ESA, and Japan contributed spacecraft. Australia; Austria; Belgium; Canada; Finland; France; Germany; Greece; Ireland; Italy; Japan; the Netherlands; Norway; Sweden; Switzerland; the United Kingdom; the United States; and the former Soviet Union participated in spacecraft development and scientific investigations.[203]

The ISTP program consisted of five spaceflight missions: two cooperative ESA/NASA missions, the SOHO and Cluster; two NASA missions, Wind and Polar; and Japan's Geotail spacecraft. NASA's contributions to Geotail, the SOHO, and Cluster were referred to as the Collaborative Solar-Terrestrial Research (COSTR) Program.[204] The scientific objectives of the ISTP program were the following:

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[203] "ISTP Unites Scientists for Study of Sun-Earth System," *NASA Facts On-Line*, NASA Goddard Space Flight Center, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/istp.htm* (accessed September 2, 2005).

[204] "ISTP Unites Scientists for Study of Sun-Earth System."

- Determine the structure and dynamics in the solar interior and their role in driving solar activity.
- Identify the processes responsible for heating the solar corona and its acceleration outward as the solar wind.
- Determine the flow of mass, momentum, and energy through geospace.
- Gain a better understanding of the turbulent plasma phenomena mediating the flow of energy through geospace.
- Implement a systematic approach to the development of the first global solar-terrestrial model, leading to a better understanding of the chain of cause-effect relationships that begins with solar activity and ends with the deposition of energy in the upper atmosphere.[205]

The GGS initiative, a subset of the ISTP program, focused on the global flow of energy from the solar wind through the three regions of geospace: the magnetosphere, ionosphere, and atmosphere. NASA contributed the Wind and Polar spacecraft to the GGS initiative, and Japan contributed Geotail. Complementary theoretical and ground-based investigations and data sets obtained from spacecraft operated by NOAA and the Los Alamos National Laboratory, also participants in the GGS program, were combined with space-based data.[206] Together, the GGS and COSTR programs were known as the ISTP program.[207]

Participants in the GGS program collaborated to obtain coordinated, simultaneous investigations of the Sun-Earth space environment over an extended time and combined their measurements to operate as a laboratory in space. The program provided the first coordinated geospace measurements of key plasma source and storage regions, performed multispectral global auroral imaging, and provided a multipoint study of Earth's magnetic response to the solar wind. The GGS program enhanced understanding of how energy and matter from the Sun influenced Earth's geospace and atmosphere and contributed to assessments of the relationship of the Sun to Earth's climate.[208] GGS program spacecraft were positioned in different regions of the magnetosphere and routinely followed events in space from their birth on the Sun, through the interplanetary medium, and then in terms of their role in creating geomagnetic storms and substorms in the near-Earth environment.

Each GGS program spacecraft was launched by NASA on Delta II rockets. Each carried a liquid propulsion system to maneuver the spacecraft to its final mission orbit and permit attitude control and stationkeeping during the mission lifetime. The two U.S. spacecraft together used 19 instruments to simultaneously measure the interaction of the solar wind with Earth's magnetic field.

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[205] "ISTP Project Overview," *http://www-istp.gsfc.nasa.gov/istp/misc/istp_project.html* (accessed April 25, 2006).

[206] The ESA's Cluster spacecraft were destroyed at launch.

[207] "Mission Operation Report, International Solar-Terrestrial Physics Program (ISTP), Geotail," Report no. S-418-92-01 (NASA History Office Electronic Document 30777).

[208] "Sciences, Aeronautics and Technology Fiscal Year 1995 Estimates," Office of Space Science, Physics & Astronomy, pp. SAT 1.1-10–SAT 1.1-11.

The GGS program science objectives were the following:

- Trace the flow of matter and energy through the geospace system from the solar wind to ultimate deposition into the atmosphere.
- Understand how the regions of geospace interact.
- Investigate the physical processes controlling the origin; entry; transport; storage; energization; and loss of plasma—high-energy, ionized gases—near Earth.
- Contribute to other Sun-Earth studies by observing solar particles and fields near Earth's orbit.[209]

The NASA portions of the GGS program, Wind and Polar, almost were canceled. In 1993, Administrator Goldin established the Program Commitment Agreement, an agreement between the NASA Administrator and the Associate Administrator to execute program requirements within particular constraints, including "specific technical and schedule commitments at a stated cost."[210] If estimated mission cost at completion exceeded the stated cost in the Program Commitment Agreement by more than 15 percent, or when any other baseline requirement was violated, it triggered an additional review by the Program Management Council. The Council was directed specifically to recommend "cancellation or continuation of programs and projects." Wind and Polar, being developed by Martin Marietta, were both experiencing development problems and cost overruns. At a review before the Program Management Council, to contain costs, the GGS project manager proposed moving ahead with Wind while delaying Polar. The Council accepted this approach. Ultimately, both Wind and Polar were completed and launched; together, they remained under the 15 percent overrun limit.[211]

Geotail

Geotail was a joint project of the ISAS of Japan and NASA that investigated the geomagnetic tail region of the magnetosphere. Geotail measured global energy flow and transformation in the magnetotail to increase understanding of fundamental magnetospheric processes, including the physics of the magnetopause, the plasma sheet, and reconnection and neutral line formations.

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[209] "ISTP Unites Scientists for Study of Sun-Earth System."

[210] NASA Handbook 7120.5, "Management of Major System Programs and Projects Handbook," November 8, 1993, (cancelled).

[211] Green and Dewhurst, "Space Physics," in Logsdon, ed., p. 171.

The ISAS designed and developed the satellite, and it carried two ISAS, two NASA, and three joint ISAS/NASA instruments. The launch, on a Delta II ELV, was the first under NASA's Medium ELV launch service contract with McDonnell Douglas Corporation.

Geotail was an element of the ISTP program. In the early phase of the program, simultaneous measurements in the key regions of geospace from Geotail and the two U.S. satellites of the GGS program, Wind and Polar, along with equatorial measurements, were used to characterize global energy transfer.

The Geotail memorandum of understanding between the ISAS and NASA was signed in December 1989 after the exchange of notes between Japan and the United States in September 1989. Geotail, along with Wind and Polar and supporting equatorial measurements, provided simultaneous data to enable study of the solar wind input to the magnetosphere and key elements of the magnetospheric response comprising geomagnetic tail energy storage, ring current energy storage, and ionospheric energy input. The SOHO (launched in 1995), an ESA/NASA cooperative mission, complemented these measurements.[212]

Geotail was a spin-stabilized spacecraft using mechanically despun antennae with a design lifetime of about four years. The nominal spin rate of the spacecraft was about 20 revolutions per minute around a spin axis maintained between 85 degrees and 89 degrees to the ecliptic plane. Real-time telemetry data transmitted in the X-band was received at the Usuda Deep Space Center in Japan. There were two tape recorders on board, each with a capacity of 450 megabits, allowing continuous data coverage. The NASA DSN collected the data in playback mode. Figure 4–41 shows the Geotail spacecraft configuration.

Mission objectives required spacecraft measurements in two orbits: a nightside double lunar swingby orbit out to distances of 220 Earth radii (1,401,620 kilometers) and a near-Earth, mid-magnetosphere orbit at about 8 Earth radii by 30 Earth radii (51,024 kilometers by 191,340 kilometers). During the initial two-year phase, the nightside orbit apogee used the Moon's gravity in a series of double-lunar-swingby maneuvers that resulted in the spacecraft spending most of its time in the distant magnetotail, where the magnetotail was stretched out as a result of the impact of the solar wind encountering Earth. The orbital period in this orbit varied from one month to four months.

Then, starting in November 1994, a series of maneuvers brought the spacecraft into its near-Earth orbit. The transition orbit lasted about three months with the apogee varying from 50 Earth radii to 30 Earth radii (318,900 kilometers to 181,340 kilometers). In February 1995, phase two began as the apogee was reduced to 30 Earth radii (181,340 kilometers) to study the near-Earth substorm processes, including neutral line formation.[213] This phase was dedicated to the study of near-Earth magnetospheric processes, including neutral line formation. In June 1997, the perigee was slightly lowered to 9 Earth radii from 9.5 Earth radii (57,402 kilometers to 60,591 kilometers) to increase the probability that the spacecraft would fly inside the dayside magnetopause. The near-tail orbit of 9 Earth radii by 30 Earth radii (57,402 kilometers by 181,340 kilometers) (with an inclination of -7 degrees to the ecliptic plane) allowed extensive study of the magnetosheath, the bow shock, and the upstream region as well.[214] See Table 4–57 for further details.

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[212] "Mission Operation Report, International Solar-Terrestrial Physics Program (ISTP), Geotail," Report no. S-418-92-01 (NASA History Office Electronic Document 30777).

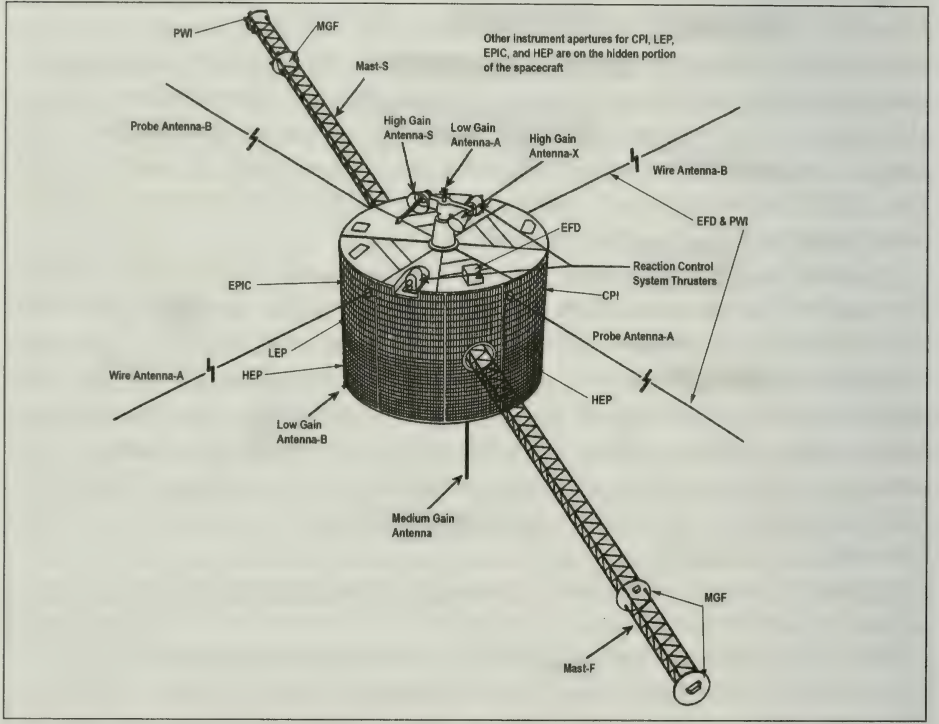
PWI
MGF
Mast-S
Other instrument apertures for CPI, LEP, EPIC, and HEP are on the hidden portion of the spacecraft
Probe Antenna-B
High Gain Antenna-S
Low Gain Antenna-A
High Gain Antenna-X
Wire Antenna-B
EFD & PWI
EFD
Reaction Control System Thrusters
EPIC
CPI
Probe Antenna-A
LEP
Wire Antenna-A
HEP
HEP
Low Gain Antenna-B
Medium Gain Antenna
MGF
Mast-F

Figure 4–41. Geotail Spacecraft Configuration.

Wind

Wind was the first of two NASA spacecraft in the GGS initiative. Wind, together with Geotail, Polar, SOHO, and Cluster projects, constituted the cooperative ISTP program. The main purpose of the Wind spacecraft was to measure the incoming solar wind, magnetic fields, and particles, although the spacecraft also observed Earth's foreshock region early in its mission.

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[213] "Geotail: Project Overview," *http://pwg.gsfc.nasa.gov/istp/geotail/geotail.html* (accessed September 2, 2005). Also "Geotail," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1992-044A* (accessed September 2, 2005).

[214] Herbert J. Kramer, "Geotail," *http://directory.eoportal.org/pres_GEOTAIL.html* (accessed September 2, 2005).

The Wind spacecraft had on-board propulsion and a design lifetime of three to five years. The cylindrical spacecraft had body-mounted solar cells to generate power, long wire spin-plane antennae, inertial booms, and spin-plane appendages to support sensors. Experiment booms were deployed along both Z axes. The spin rate was 20 revolutions per minute around an axis within 1 degree of normal to the ecliptic. Data was stored using on-board tape recorders and relayed to NASA's DSN at either 5.5 kbps or 11.1 kbps. Wind had eight science instruments, including one from France and one from the Soviet Union. It was the first time that a Soviet instrument had flown on an American spacecraft. The instrument, known as KONUS, was a gamma-ray burst experiment first proposed by the Soviet Union in 1989. The KONUS cooperative agreement was carried out under the auspices of the U.S.-U.S.S.R. joint working group on Space Astronomy and Astrophysics.[215] Figure 4–42 shows a diagram of the spacecraft.

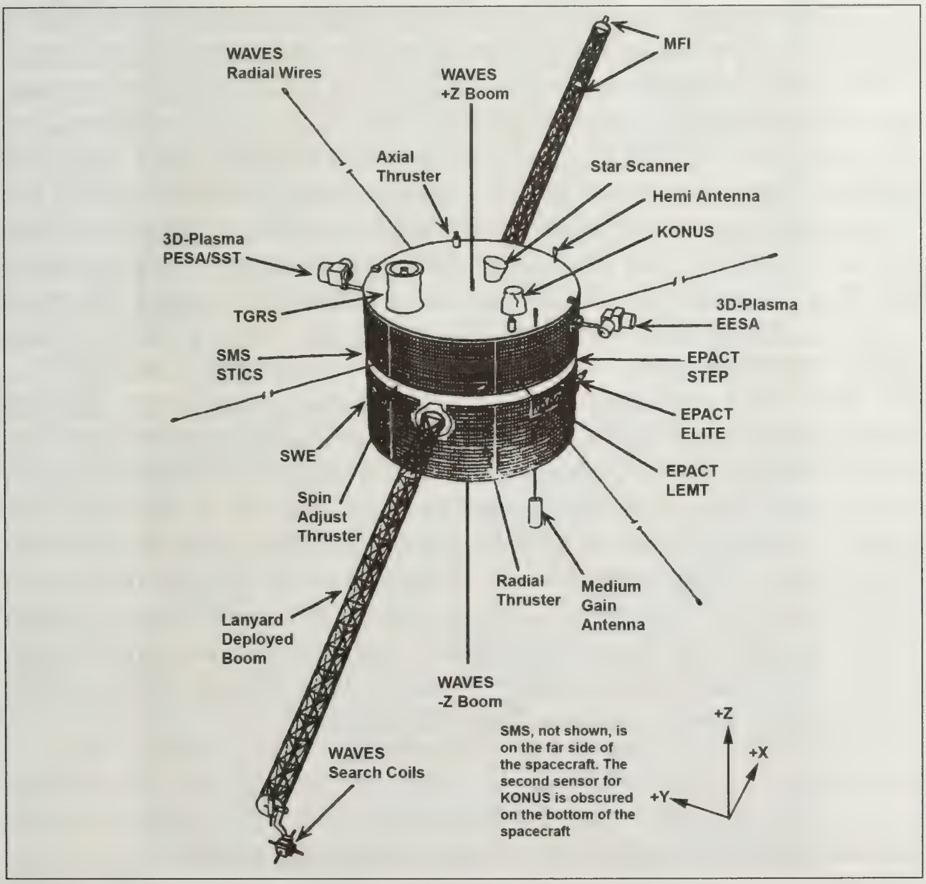
WAVES Radial Wires
WAVES +Z Boom
MFI
Axial Thruster
Star Scanner
Hemi Antenna
KONUS
3D-Plasma PESA/SST
TGRS
3D-Plasma EESA
SMS STICS
EPACT STEP
EPACT ELITE
SWE
EPACT LEMT
Spin Adjust Thruster
Radial Thruster
Medium Gain Antenna
Lanyard Deployed Boom
WAVES -Z Boom
WAVES Search Coils
SMS, not shown, is on the far side of the spacecraft. The second sensor for KONUS is obscured on the bottom of the spacecraft
+Z
+X
+Y

Figure 4–42. Wind Spacecraft.

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[215] "Soviet Scientists and ISTP Partners Visit Goddard," *Goddard News* 36, no. 4 (April 1990): 8. (NASA History Office Folder 5910).

Some of the instruments aboard Wind measured properties of the solar wind plasma, including the speed of the plasma's flow, the flow's direction, and the distribution of electron and ion energies. The instruments also measured the proportions of various ions in the solar wind: protons and alpha-particles were most abundant, but the stream also included the more rare isotopes of "heavy" hydrogen and "light" helium, as well as carbon, oxygen, and other elements. The variation of these proportions shed light on processes in the Sun's corona, where the solar wind originated.

Radio wave receivers monitored emissions from the Sun and from space plasmas, and a magnetometer sampled the IMF up to 44 times a second. Because the IMF was very weak (about 1/10,000 of Earth's surface field), the magnetic fields produced by electric currents on the spacecraft were strong enough to disturb its observation, and the magnetometer was therefore placed at the end of a long boom, away from the interference. Wind also carried two gamma-ray detectors to observe and time gamma-ray bursts from distant space, probably beyond our galaxy.[216] See Table 4–58 for further information.

For the first nine months of the mission, Wind was placed in a double lunar swingby orbit near the ecliptic plane, with apogee from 80 Earth radii to 250 Earth radii (382,600 kilometers to 1,594,500 kilometers) and perigee of between 5 Earth radii and 10 Earth radii (31,890 kilometers and 63,780 kilometers). In this orbit, lunar gravity assists kept Wind's apogee over the day hemisphere of Earth, and magnetospheric observations were made. Wind was then inserted into a small halo orbit, about the sunward Sun-Earth gravitational equilibrium point (L1 Lagrangian point), varying from 235 Earth radii to 265 Earth radii (1,498,830 kilometers to 1,690,170 kilometers).[217] In this orbit, Wind continuously measured the incoming solar wind, magnetic fields, and particles while providing a warning of approximately 1 hour to the other ISTP spacecraft of changes in the solar wind.[218] After several months at this location, Wind made two passes by the Moon, and in October 1998, began a six-month series of "petal" orbits that took the spacecraft out of the ecliptic phase. These orbits brought Wind as close as 10 Earth radii (about 63,780 kilometers) and as far as 80 Earth radii (510,240 kilometers) from Earth. The orbit took Wind at an angle of 60 degrees from the ecliptic plane, allowing the spacecraft to sample regions of interplanetary space and the magnetosphere that had not been studied before.[219]

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[216] "WIND," *http://www.phy6.org/Education/wwind.html* (accessed October 25, 2005).

[217] The Earth-Sun L1 point is 1 percent of the way to the Sun, four times the distance from Earth to the moon, or about one million miles away from Earth. The solar wind reaches L1 about 1 hour before it reaches Earth, making it a good place to observe changes in solar activity before it affects Earth. From the L1 Home Page, *http://triana.gsfc.nasa.gov/instruments/lagrange.htm* (accessed August 8, 2005).

[218] "Wind," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1994-071A* (accessed September 27, 2005).

[219] "ISTP Science News," April 1998, *http://pwg.gsfc.nasa.gov/istp/news/9804* (accessed September 27, 2005).

Polar

The Polar satellite was the second of two NASA spacecraft in the GGS program. It was launched in early 1996 after delays caused by cost overruns; suspected faulty components; a failure of the launch vehicle's solid rocket motor separation system on an earlier Delta launch that delayed launches until resolution of the problem; and the precedence of other missions. When finally launched, the Polar satellite set a new record for back-to-back launches of the Delta II, coming just seven days after launch of the NEAR spacecraft.[220]

The primary objective of the Polar mission was to study aurora light and other electromagnetic radiation emissions and characterize the solar particles present within the magnetosphere over Earth's polar regions. The Polar satellite was launched into a large elliptical orbit that looped over the poles for a three-year mission. The Polar satellite made its observations as its orbit precessed with time, observed the equatorial inner magnetosphere, and progressed toward an extended Southern Hemisphere campaign. Polar gave scientists new perspectives on how the constant bombardment from radiation and particles from the Sun affected Earth's space environment, data that eventually could help scientists forecast "space weather."[221]

Within the fleet of spacecraft studying the Sun-Earth connection, Polar was responsible for multi-wavelength imaging of the aurora, measuring the entry of plasma into the polar magnetosphere and the geomagnetic tail, the flow of plasma to and from the ionosphere, and the deposition of particle energy in the ionosphere and upper atmosphere.

Polar was a spin-stabilized, cylindrical-shaped spacecraft flying in a highly eccentric polar orbit to survey the ionosphere and upper atmosphere. The reinforced structure carried the scientific instruments, support subsystems, and body-mounted solar array panels. Openings in the solar array provided viewing ports required for radial viewing instruments. A despun platform provided an inertially stable mounting surface for four instruments, the Visible Imaging System (VIS), Ultraviolet Imager (UVI), Polar Ionospheric X-ray Imaging Experiment (PIXIE), and Comprehensive Energetic Particle Pitch Angle Distribution/Source-Loss Cone Energetic Particle Spectrometer (CEPPAD/SEPS). These instruments provided multispectral images of the aurora and measurements of high-energy ion composition.

The Despun Platform Mechanism (DPM) performed orientation and control of the despun platform. The DPM was a high-precision electromechanical device maintaining continuous near-inertial orientation of the platform while the main body of the spacecraft rotated at 10 revolutions per minute. Honeywell Satellite Systems Operations designed and built the DPM.

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[220] Joel W. Powell, "Geospace Observed: Secrets of Aurora Probed by Polar Satellite," *Spaceflight* 38 (November 1996): 370–372.

[221] "Polar Launch Completes Global Geospace Science Program Missions," Goddard News Release 96-008, February 7, 1996, *http://www.gsfc.nasa.gov/news-release/releases/1996/96-008.txt* (accessed August 10, 2005).

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In 1997, Polar started viewing the Hale-Bopp comet. Hale-Bopp crossed the orbital plane of Polar on April 1, 1997, and was within the FOV of the imagers, the VIS, UVI, and PIXIE, from March 27 to April 2. They imaged the comet during its closest approach to the Sun (its perihelion) in a wide wavelength range covering the visible through x-ray bandwidths, something no other imaging system could do. Polar's specialized cameras had sensitivities in different wavelengths: the VIS observed the comet with one far UV and 10 visible filters. At the same time, the UVI imaged with four filters sensitive in different bands of the far UV; the PIXIE obtained an upper limit on the x-ray flux from the comet.[222] Figure 4–43 shows the position of Polar's instruments. Table 4–59 provides further mission details.

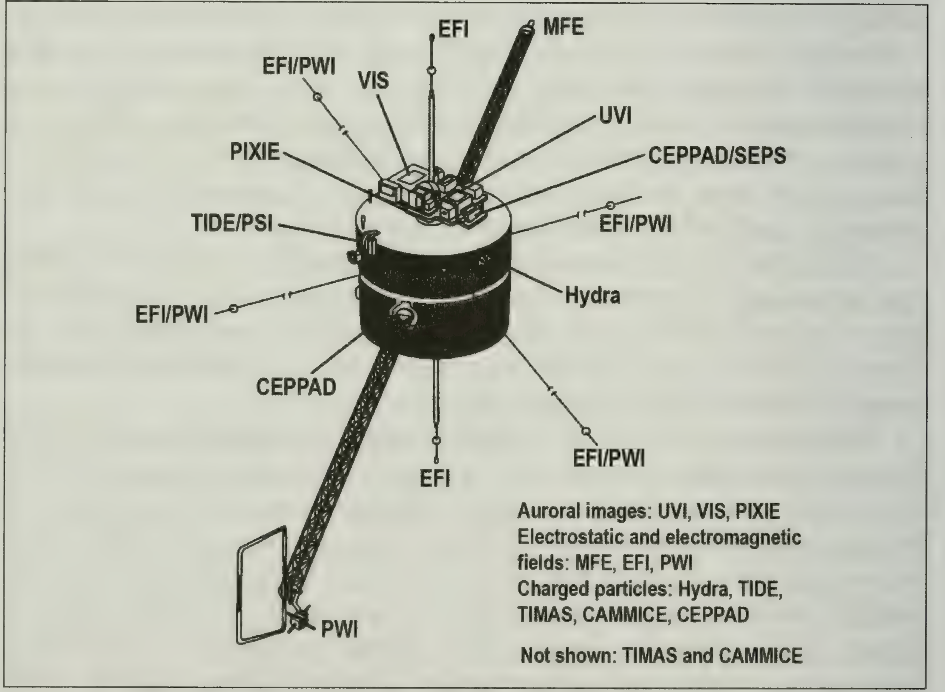
EFI
MFE
EFI/PWI
VIS
UVI
PIXIE
CEPPAD/SEPS
TIDE/PSI
EFI/PWI
Hydra
EFI/PWI
CEPPAD
EFI/PWI
EFI
PWI
Auroral images: UVI, VIS, PIXIE
Electrostatic and electromagnetic fields: MFE, EFI, PWI
Charged particles: Hydra, TIDE, TIMAS, CAMMICE, CEPPAD
Not shown: TIMAS and CAMMICE

Figure 4–43. Location of Polar Instruments.

Solar and Heliospheric Observatory

The SOHO was an international cooperative mission between the ESA and NASA and part of the ISTP program. The ESA and NASA signed the memorandum of understanding for the SOHO in December 1989. The observatory consisted of a three-axis stabilized ESA spacecraft with shared

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[222] "Comet Hale-Bopp's into the Polar Satellite Field-of-View," *http://pwg.gsfc.nasa.gov/istp/events/halebopp/incoming/press/press.html* (accessed August 10, 2005).

NASA and ESA solar physics telescopes and plasma physics fields and particles instrumentation. The two agencies shared tracking and data acquisition. NASA conducted mission operations.

The SOHO was launched December 2, 1995 on an Atlas IIAS ELV. The SOHO observed the Sun 24 hours a day and without interruption from its orbit around the L1 libration point, which it reached on February 14, 1996. The spacecraft returned its first image on December 19, 1995, and it was declared operational by April 16, 1996.[223]

The main scientific purpose of the SOHO was to study the Sun's internal structure by observing velocity oscillations and radiance variations and to examine the physical processes forming and heating the Sun's corona and giving rise to the solar wind. The SOHO used imaging and spectroscopic diagnosis of the plasma in the Sun's outer regions coupled with in situ measurements of the solar wind. It was also the most prolific comet-finder ever.

The three-axis stabilized Sun-pointing spacecraft had two modules. The service module formed the lower portion of the spacecraft. The service module provided power, thermal control, telecommunications, and pointing for the entire spacecraft, as well as support for the solar panels. The payload module sat above the service module and housed the 12 scientific instruments developed and furnished by 12 international consortia involving 29 institutes from 15 countries. U.S. scientists led three consortia; European scientists led nine consortia. More than 1,500 scientists in countries around the world were either directly involved in the SOHO's instruments or used SOHO data in their research programs. NASA's DSN tracked the spacecraft beyond Earth's orbit.

The SOHO successfully completed its primary mission in April 1998. Major science highlights to that time included the following:

- Detection of plasma rivers beneath the surface of the Sun.
- Discovery of a magnetic "carpet" on the solar surface seeming to account for a substantial part of the energy needed to cause the very high temperature of the Sun's corona.
- The first detection of flare-induced solar quakes.
- Discovery of more than 50 sungrazing comets.
- The most detailed view to date of the solar atmosphere.
- Spectacular images of coronal mass ejections, which were used to improve the ability to forecast space weather.[224]

Figure 4–44 shows a series of SOHO images taken on February 11, 1996.

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[223] Asif Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, Monographs in Aerospace History no. 24 (Washington, DC: National Aeronautics and Space Administration, 2002), pp. 159–160.

[224] "SOHO Spacecraft Observations Interrupted," *NASA News* Release 98-112, June 26, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-112.txt* (accessed August 8, 2005).

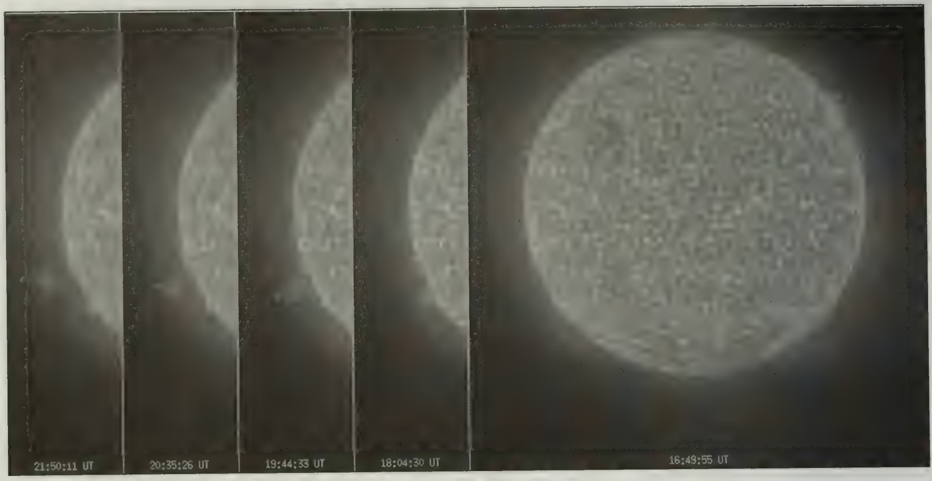

Figure 4–44. SOHO took this sequence of images with the Extreme Ultraviolet Imaging Telescope. Visible on the lower left is an "eruptive prominence," or blob, of 60,000°F (33,315°C) gas measuring more than 80,000 miles (128,747 km) long. When SOHO took the image on February 11, 1996, the blob was traveling at more than 15,000 miles per hour (24,140 km per hour). Eruptions such as these occur when a significant amount of cool dense plasma or ionized gas escapes from low-level magnetic fields in the Sun's atmosphere. When they occur, they sometimes disrupt power and communications. (NASA Photo No. GSFC 091)

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In December 1997, a key event in solar physics occurred when SOHO scientists discovered "jet streams" or "rivers" of hot, electrically charged plasma flowing beneath the surface of the Sun. These new findings helped scientists understand the 11-year sunspot cycle and associated increases in solar activity that disrupted Earth's power and communications systems.[225]

Ground controllers lost contact with the SOHO during maintenance operations on June 24, 1998. The SOHO went into emergency Sun reacquisition mode, which occurs when an anomaly causes the spacecraft to lose its orientation toward the Sun. The spacecraft fired its attitude control thrusters under the guidance of an on-board Sun sensor in an effort to point itself toward the Sun again. A month later, on July 27, ground-based radio telescopes detected and found the spacecraft near its original position in space, turning slowly at a rate of roughly one revolution per minute. On August 3, the SOHO answered signals sent to it through the DSN station at Canberra, Australia. Coming intermittently in the form of bursts of signal lasting from 2 to 10 seconds with no data, the signals showed that the spacecraft was still capable of receiving and responding to ground commands. On August 8, the first telemetry from the SOHO indicated that its service module was "very cold." Over the next two days, the spacecraft sent temperature and electrical data to ground controllers, signaling low, high, and normal temperatures from its scientific instruments. Further, the hydrazine fuel used by its thrusters was partially frozen. Thawing the fuel took nearly three weeks, which was followed by warming the pipes that carried the fuel to the thrusters. By September 3, the propulsion system had been fully thawed, and sunlight was hitting the solar panels at a slant angle of nearly 60 degrees. The batteries were recharged and had a full charge by September 8.[226]

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[225] "Chronology of Defining Events in NASA History," *http://history.nasa.gov/Defining-chron.htm* (accessed August 8, 2005).

On September 16, the SOHO obeyed commands to stop spinning and turned its face and solar panels fully toward the Sun for the first time since June 24, when it spun out of control and lost contact. By the second week in October, scientists released high-quality. new pictures of the Sun taken from the SOHO. On October 14, the project announced that 9 of the 12 instruments had been successfully reactivated. Before the end of the month, the remaining instruments were successfully reactivated.[227]

The spacecraft had a second brief crisis on December 21, 1998, when it went into emergency Sun reacquisition mode because the last of its three gyroscopes failed. To stop the rapid depletion of fuel caused by continually firing on-board jets to keep the spacecraft's sensors pointed toward the Sun, engineers designed software to enable the spacecraft to resume science operations without gyroscopes. Beginning on February 2, 1999, the spacecraft was reprogrammed to ignore faulty information from the gyroscopes and use new software sent by ground controllers. This was the first time that a spacecraft equipped with gyroscopes continued working without them.[228] Table 4–60 provides further mission details.

Solar-A/Yohkoh

Solar-A was a cooperative mission of Japan, the United States, and the United Kingdom. The mission's prime purpose was to study high-energy phenomena in solar flares during the period of maximum solar activity. The mission was a successor to Hinotori, an earlier Japanese spacecraft flown at the previous solar activity maximum in 1981. One of the four instruments on Yohkoh, the Soft X-ray Telescope (SXT), was the product of international collaboration between the United States and Japan. Solar-A was renamed Yohkoh after successfully achieving orbit. Yohkoh means "sun-ray" or "sunbeam" in Japanese.

Yohkoh was a three-axis stabilized satellite carrying four instruments: two imagers and two spectrometers. The imaging instruments, the SXT and the Hard X-ray Telescope (HXT), had almost full Sun fields of view to avoid missing any flares on the visible disk of the Sun; they were in sunlight for 65 minutes to 75 minutes of each 90-minute orbit period. The SXT acquired its first image of the Sun on September 30, 1991. The HXT acquired its first image data on October 3, 1991. The sensitivity of HXT was approximately 100 times that of its predecessor instrument on the Solar Maximum Mission spacecraft, and approximately 10 times the sensitivity of the x-ray imager aboard the Hinotori spacecraft.[229] Production and data analysis for the SXT was a collaboration between Japanese scientists at the National Astronomical Observatory of Japan and U.S. solar physicists at the Lockheed Palo Alto Research Laboratory. The spectrometers were the Bragg Crystal Spectrometer (BCS) (developed by the National Astronomical Observatory of Japan in collaboration with the United Kingdom Science and Engineering Research Council, the U.S. National Institute of Standards and Technology, and the U.S. Naval Research Laboratory) and the Wide Band Spectrometer (WBS) (developed by Japan's Institute of Space and Astronautical Science).[230]

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[226] "SOHO Is Pointing at the Sun Again," ESA Press Release no. 33-1998, September 17, 1998, *http://www.esa.int/esaCP/Pr_33_1998_p_EN.html* (accessed August 8, 2005).

[227] F.C. Vandenbussche, "SOHO's Recovery–An Unprecedented Success Story," from *ESA Bulletin* 97, (March 1999): 39 *http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31893* (accessed July 7, 2006).

[228] "SOHO Gets Back to Work: Historic First in Space," ESA Press Release no. 05-99, February 3, 1999, *http://www.esa.int/esaCP/Pr_5_1999_p_EN.html* (accessed August 8, 2005).

The spacecraft structure consisted of a main body and six solar panels. A combination of passive and active methods provided spacecraft thermal control. Multilayer thermal blankets and thermal radiators were used for passive thermal control. Heaters with thermostats controlled the temperature of the batteries, the star tracker, and the SXT.

The spacecraft flew in a slightly elliptical low-Earth orbit. During five to six of its orbits each day, Yohkoh passed through the radiation belts of the South Atlantic Anomaly where the BCS, HXT, and most channels on the WBS (all of which used high voltages) had to be turned off to avoid damage to the instruments and satellite.

Observations from the instruments were stored in the Spacecraft Bubble Data Recorder (BDR). Approximately 50 megabytes of data were accumulated each day and stored in the 10-megabyte on-board tape recorder. To optimize the recorder, the BDR could operate at several bit-rates—high, medium, and low. Switching between the bit-rates was controlled both automatically and by on-board deferred commands. This switching was necessary because the high bit rate held only 42 minutes of data. Some overwriting of data was permitted.

The satellite operated in several spacecraft and subsystem modes. The two modes of principal interest were the Quiet Mode and Flare Mode. Switching between these two particular modes was controlled by a flare flag generated by the WBS. Yohkoh's operating mode determined which instruments could collect the data and how much they could collect. Generally, more HXT data was taken during the Flare Mode than during the Quiet Mode.

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[229] "Hard X-Ray Telescope," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-062A&ex=1* (accessed September 26, 2005).

[230] "Solar-A Mission Operation Report," Report no. S-416-91-01, (NASA History Office Folder 14684).

During each orbit, Yohkoh passed over the Kagoshima Space Center in Japan. Commanding of the satellite could be performed at that time. The rest of the time the satellite was controlled by on-board deferred command storage. In addition, Kennedy Space Center received current data from the BDR. At other locations in the orbit, the data was sent to ground stations in NASA's DSN. Figure 4–45 shows the solar cycle as a mosaic of Yohkoh images gathered between 1991 and 1999. Table 4–61 provides further mission details.

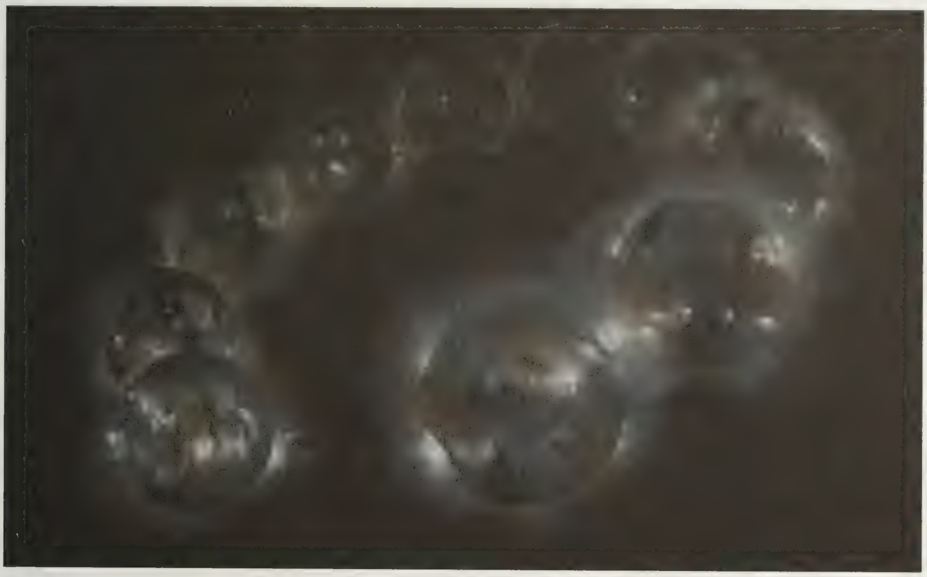

Figure 4–45. This mosaic of Yohkoh images shows the changing appearance of the solar corona during a solar activity cycle. Beginning in late 1991, these x-ray images depict the million-degree plasma of the Sun's atmosphere as it evolved from high activity (many hot active regions in the left-hand image), to very low activity (1995–1996, upper right-hand images), and back to high activity (1999, front image near center). Because only very hot plasmas emit x-rays, the much cooler surface of the Sun appears as a dark sphere underneath the radiating corona.[231]

Ongoing Physics and Astronomy Missions

Two physics and astronomy missions launched before 1989 continued to operate into the 1990s.

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[231] The solar x-ray images are from the Yohkoh mission of ISAS, Japan. The x-ray telescope was prepared by the Lockheed Palo Alto Research Laboratory, the National Astronomical Observatory of Japan, and the University of Tokyo with the support of NASA and ISAS.

Interplanetary Monitoring Platform (IMP)-8

The IMP-8 satellite, also called Explorer 50, was the last in a family of 10 IMPs. The IMP-8 was launched on October 26, 1973, into a nearly circular orbit about Earth at a radius of about 35 Earth radii (223,230 kilometers).[232] It spent 60 percent or more of each 12-day orbit in the solar wind and the rest of its time in the magnetosheath and magnetosphere. The IMP-8 was a spin-stabilized spacecraft, with its spin vector nearly perpendicular to the ecliptic plane, and a spin rate of 24 revolutions per minute.[233] Telemetry coverage was 90 percent in the early years, but only 60 to 70 percent through most of the 1980s and early 1990s. Coverage returned to the 90 percent range in the mid to late 1990s.

The IMP-8 was a drum-shaped spacecraft, 135.6 centimeters (53.4 inches) across and 157.4 centimeters (62 inches) high, instrumented for interplanetary and magnetotail studies of cosmic rays, energetic solar particles, plasma, and electric and magnetic fields.[234]

Experiments on the spacecraft were the following: 1) Magnetic Field Experiment (magnetometer); 2) Solar Plasma Faraday Cup; 3) Solid-State Detectors; 4) Measurement of Low-Energy Protons and Electrons; 5) Energetic Electrons and Protons (also called the Energetic Particle Experiment); 6) Electrons and Hydrogen and Helium Isotopes; 7) Cosmic Ray Nuclear Composition; 8) Solar and Cosmic-Ray Particles; 9) Charged Particle Measurements Experiment; 10), Solar Plasma Electrostatic Analyzer; 11) Electrostatic Fields; and 12) Electrostatic Waves and Radio Noise.

The IMP's magnetometer failed on June 10, 2000. The Charged Particle Measurements Experiment and the Energetic Particle Experiment operated successfully for 28 years and generated high-quality data leading to new discoveries and resulting in hundreds of publications. Both instruments continued to perform without problems until NASA terminated IMP-8 operations as an independent mission at the end of October 2001.[235] Telemetry acquisition resumed after about three months at the Canberra, Australia, ground station only (30 to 50 percent coverage) as an adjunct to the Voyager and Ulysses missions. As of August 2005, the IMP-8 continued in this mode.[236]

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[232] The NSSDC Master Catalog Database says that IMP-8's initial orbit "was more elliptical than intended, with apogee and perigee distances of about 45 and 25 Earth radii" and "its eccentricity decreased after launch." *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-078A* (accessed October 20, 2005).

[233] "IMP-8 Charged Particle Measurement Experiment (CPME) and Energetic Particle Experiment (EPE)," *http://sd-www.jhuapl.edu/IMP/imp_index.html* (accessed October 20, 2005).

[234] "IMP-J," NSSDC Master Catalog Display: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-078A* (accessed October 20, 2005).

[235] "IMP-8 Charged Particle Measurement Experiment (CPME) and Energetic Particle Experiment (EPE)," *http://sd-www.jhuapl.edu/IMP/imp_index.html* (accessed October 20, 2005).

[236] "IMP-J," NSSDC Master Catalog Display: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1973-078A* (accessed October 20, 2005).

The IMP-8 was an important adjunct to the ISTP program. The IMP-8 provided in-ecliptic, one Astronomical Unit (AU) baseline data for the deep-space Voyager and Ulysses missions, and it accumulated a long time-series database useful in understanding long-term solar processes.[237]

International Ultraviolet Explorer

The International Ultraviolet Explorer (IUE) was launched into geosynchronous orbit at the end of NASA's second decade on January 26, 1978.[238] Totally dedicated to UV astronomy, the satellite operated for more than 18 years, long after its three-year to five-year expected lifetime. The spacecraft made the last of its astrophysical observations on September 27, 1996. The IUE remained operational until its hydrazine was deliberately vented and batteries were drained. The IUE transmitter turned off on September 30, 1996, after it received its final command to "shut down."[239]

The IUE was one of the most productive astronomical telescopes ever. Its 18 years and 8 months of operations returned 104,470 high-resolution and low-resolution spectra of 9,600 astronomical sources from all classes of celestial objects in the 1,150-angstrom to 3,350-angstrom UV band. These were transformed into 111,000 spectral files collected together and accessible worldwide through the ESA's IUE Newly Extracted Spectra (INES) system. The Laboratory for Space Astrophysics and Theoretical Physics in Spain operated the IUE INES for the astronomical community in close collaboration with the Canadian Astronomical Data Centre in Victoria, British Columbia. NASA maintains an IUE archival site, under the Multimission Archive at the Space Telescope Science Institute in Baltimore, Maryland.[240] Figure 4–46 shows IUE satellite-recorded spectra.

The IUE was a three-way collaborative project among NASA, the ESA, and the British Science and Engineering Research Council (later named the Particle Physics and Astronomy Research Council). The IUE operated in a real-time mode similar to ground-based observatories and was the only geosynchronous astronomy satellite capable of continuous observation 24 hours daily. More available observing hours per day and per year allowed researchers to explore and test ideas that may not have been possible with more restricted observing time.[241] Until October 1995, the IUE operated continuously, controlled 16 hours daily from Goddard Space Flight Center and 8 hours daily from the ESA facility at Villafranca, Spain. After October 1995, the operational scheme changed so that science operations were fully controlled from Villafranca, with 16 hours daily devoted to scientific operations and 8 hours daily in the low-quality part of the orbit used for spacecraft housekeeping.[242] About two-thirds of the observing time was allocated through NASA's competitive guest observer program with the remainder allocated through the ESA's equivalent program.[243]

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[237] "IMP-8 Project Information," *http://nssdc.gsfc.nasa.gov/space/imp-8.html* (accessed October 20, 2005).

[238] Details of the IUE project can be found in Rumerman, *NASA Historical Data Book, Volume V, 1979–1998* (Washington, DC: National Aeronautics and Space Administration Special Publication-4012, 1999), pp. 399–401.

[239] Joseph King and Michael Van Steenberg, "IUE Final Archive Creation and Future Management: IUE, NSSDC, and STScI Roles," *NSSDC News* 14 (June 1998), *http://nssdc.gsfc.nasa.gov/nssdc_news/june98/01_j_king_0698.html* (accessed September 30, 2005).

[240] "IUE Science Results," ESA, *http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31290* (accessed September 30, 2005).

[241] Y. Kondo, "Space Astronomy and IUE," in *Ultraviolet Astrophysics Beyond the IUE; Final Archive*, Proceedings of the Conference held in Sevilla, Spain, November 11–14, 1997 (The Netherlands: European Space Agency Special Publication-413, ESA Publications Division, 1998).

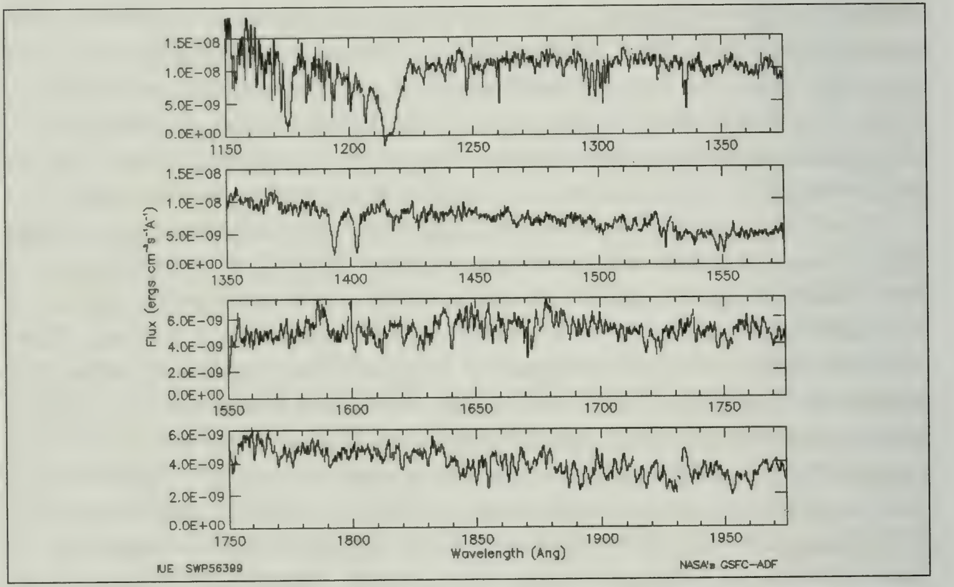

Figure 4–46. The IUE satellite recorded spectra in the UV wavelength region. The spectra (light flux versus wavelength) contain many absorption lines, or dips of flux at certain wavelengths. The strengths of these lines contain information about an astronomical object's chemical composition, the physical conditions such as temperature and pressure on the surface, and the component of any motion (the radial velocity) on the surface directed toward the external observer. (Credit: MAST/D. Massi)

During its lifetime, the IUE served more than 2,000 guest observers from around the world, including astronomers from North and South America; Europe; China; India; Russia; Africa; and Australia. Approximately 3,500 scientific articles in peer-reviewed journals were written based on IUE observations, more than any other satellite observatory to that time.[244] More than 1,000 European observing programs were conducted from the ESA's "IUE

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[242] "INES, IUE Newly Extracted Spectra," *http://ines.vilspa.esa.es/ines/Ines_PCentre/iue.htm* (accessed July 18, 2006).

[243] King and Van Steenberg, "IUE Final Archive Creation and Future Management: IUE, NSSDC, and STScI Roles," *NSSDC News* 14 (June 1998), *http://nssdc.gsfc.nasa.gov/nssdc_news/june98/01_j_king_0698.html* (accessed September 30, 2005).

[244] Jim Sahli, "IUE 'Lights Out,'" *Goddard News* 43 (November 1996): 5 (NASA History Office Folder 6079).

Observatory" at the Villafranca Satellite Tracking Station in Spain. The IUE was the first satellite designed as a common facility to be used by the world community of observers, the first scientific satellite to allow visiting astronomers to make real-time observations of UV spectra, and the first astronomical and satellite facility to deliver fully reduced data within 48 hours to the worldwide science community. The IUE also led to creation of the first worldwide astronomical reduced-data archive delivering 44,000 spectra per year (5 spectra per hour) to astronomers in 31 countries.[245] NASA maintains an IUE archival site, under the Multimission Archive at the Space Telescope Science Institute in Baltimore, Maryland. The project has received numerous recognitions during its lifetime, including the U.S. Presidential Award for Design Excellence, awarded to the IUE in 1988 during its 10th anniversary year.[246]

The spacecraft's only serious problems stemmed from the failures of five of the six gyroscopes in its ACS, occurring in 1979, 1982, 1982, 1985, 1991, and 1996. When the fourth gyroscope failed in 1985, the IUE continued operations owing to an innovative reworking of its ACS that substituted the fine Sun sensor. Even when the fifth gyroscope was lost in 1995, the IUE could still be stabilized in three axes (with only a single gyroscope) by adding star tracker measures.

During its lifetime, the IUE greatly surpassed its original science goals. Despite the value of the Hubble Space Telescope, which was launched in 1990, the IUE retained its importance because it covered the entire spectral region in ways not possible with the Hubble Space Telescope's high-resolution spectrographs in low-Earth orbit. The combination of the IUE and the Hubble Space Telescope provided a very efficient complementary function for astronomers.[247] The IUE's major scientific discoveries, taken from the INES Principal Centre, were the following:

- First detection of the existence of an aurora in Jupiter
- First detection of sulfur in a comet
- First quantitative determination of H_2O (water) loss in a comet (some 10 tons per second)
- First evidence for strong magnetic fields in chemically peculiar stars
- First orbital radial velocity curve for a WR (Wolf-Rayet) star allowing its mass determination
- First detection of hot dwarf companions to Cepheid variables
- First observational evidence for semi-periodic mass loss in high mass stars
- First discovery of high-velocity winds in stars other than the Sun

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[245] "INES, IUE Newly Extracted Spectra," *http://ines.vilspa.esa.es/ines/Ines_PCentre/iue.html* (accessed September 7, 2005).

[246] Kondo, "Space Astronomy and IUE," in *Ultraviolet Astrophysics Beyond the IUE; Final Archive.*

[247] "IUE Science Results," ESA, *http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=31290* (accessed September 30, 2005).

- First identification of the progenitor of any supernova in history (Supernova 1987A)
- Discovery of starspots on late type stars through Doppler mapping techniques
- Discovery of large-scale motions in the transition regions of low-gravity stars
- Discovery of high temperature effect in stars in the early stages of formation
- Discovery of high-velocity winds in cataclysmic variables
- Discovery of the effect of chemical abundance on the mass loss rate of stars
- First determination of a temperature and density gradient in a stellar corona outside the Sun
- First detection of gas streams within and outflowing from close binary stars
- The determination that no nova ejects material with solar abundance
- Discovery of the "O-Ne-Mg" (oxygen-neon-magnesium) novae, where the excess of these elements can be directly traced to the chemical composition of the most massive white dwarfs
- Discovery of a ring around Supernova 1987A, a leftover from previous evolutionary stages
- First direct detection of galactic halos
- First observations of extragalactic symbiotic stars
- First uninterrupted light curves of stars for more than 24 hours continuously
- First detection of photons at wavelengths less than 50 nanometers from any astronomical source apart from the Sun
- First direct determination of the size of the active regions in the nuclei of Seyfert galaxies (mini-quasars)
- First detection of a transparent sightline to a quasar at high redshift, allowing the first abundance determination of the intergalactic medium in the early universe

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Suborbital Program

NASA's suborbital program used balloons, aircraft, and sounding rockets to conduct versatile, relatively low-cost research of Earth's ionosphere and magnetosphere; space plasma physics; stellar astronomy; solar astronomy; and high-energy astrophysics. Activities were conducted on both a national and international cooperative basis. The physics and astronomy program funded suborbital missions.

Sounding rockets carried scientific instruments into space along parabolic trajectories, providing nearly vertical traversals along their upleg and downleg while appearing to "hover" near their apogee location. The overall time in space was typically only 5 minutes to 20 minutes, for a well-placed scientific experiment, and the short time and low vehicle speeds were completely adequate (and sometimes ideal) to carry out a successful scientific experiment. Some important regions of space were too low to be sampled by satellites, so sounding rockets provided the only platforms that could carry out direct *in situ* measurements in these regions.

The sounding rocket program served as a less costly testbed for new scientific techniques, scientific instrumentation, and spacecraft technology eventually flown on numerous satellite missions. For example, COBE; CGRO; EUVE; FAST; ASTRO-2; UARS; SOHO; TRACE; and numerous other NASA satellite missions were enabled by technology and techniques developed in the suborbital program. The low cost of sounding rocket access to space fostered the following innovation: instruments and/or technologies which were not sufficiently developed to warrant the investment of satellite-program scale funding were often "prototyped" with initial space testing on sounding rockets.

Sounding rockets offered the following advantages:

- Quick, low-cost access to high altitudes where optical observations of astronomical, solar, and planetary sources could be made of radiation at wavelengths absorbed by Earth's lower atmosphere.
- Direct access to Earth's mesosphere and lower thermosphere (40 kilometers to 120 kilometers) (25 miles to 75 miles).
- Low cost.
- Rapid response times.
- Ability to fly relatively large payload (>500 kilograms) (1,102 pounds) masses on inexpensive vehicles.
- Provision of several minutes of ideal, "vibration-free" microgravity.
- Ability to use Earth's limb as an occulting disk to observe astronomical sources close to the Sun.
- Ability to gather *in situ* data in specific geophysical targets such as the aurora; the cusp; the equatorial electrojet; noctilucent clouds; and thunderstorms.
- Access to remote geophysical sites and southern hemisphere astronomical objects.
- Dwell times of several minutes at apogee.
- Slow vehicle speed with respect to the ambient medium (and much slower than that of orbiting satellites).
- Collection of vertical profiles of geophysical parameters.
- Ability to fly simultaneous rockets along different trajectories (e.g., with different apogees, flight azimuths).
- Ability to fly numerous free-flying sub-payloads from a single launch vehicle.
- Ability to recover and refly instruments.

NASA used 13 launch vehicles in the NASA Sounding Rocket Program. All NASA sounding rocket launch vehicles used solid propellant propulsion systems. Extensive use was made of 20-year-old to 30-year-old military surplus motors in 10 of the systems. All vehicles were unguided except those using the S-19 Boost Guidance System. During flight, all launch vehicles were given a spinning motion to reduce potential dispersion of the flight trajectory due to vehicle misalignments.[248]

Figure 4–47 shows the four-stage Black Brant, one of NASA's commonly used sounding rocket models. At 66 feet (20 meters) tall, this rocket could carry scientific payloads weighing up to 1,213 pounds (550 kilograms) to altitudes of 800 miles (1,287 kilometers).

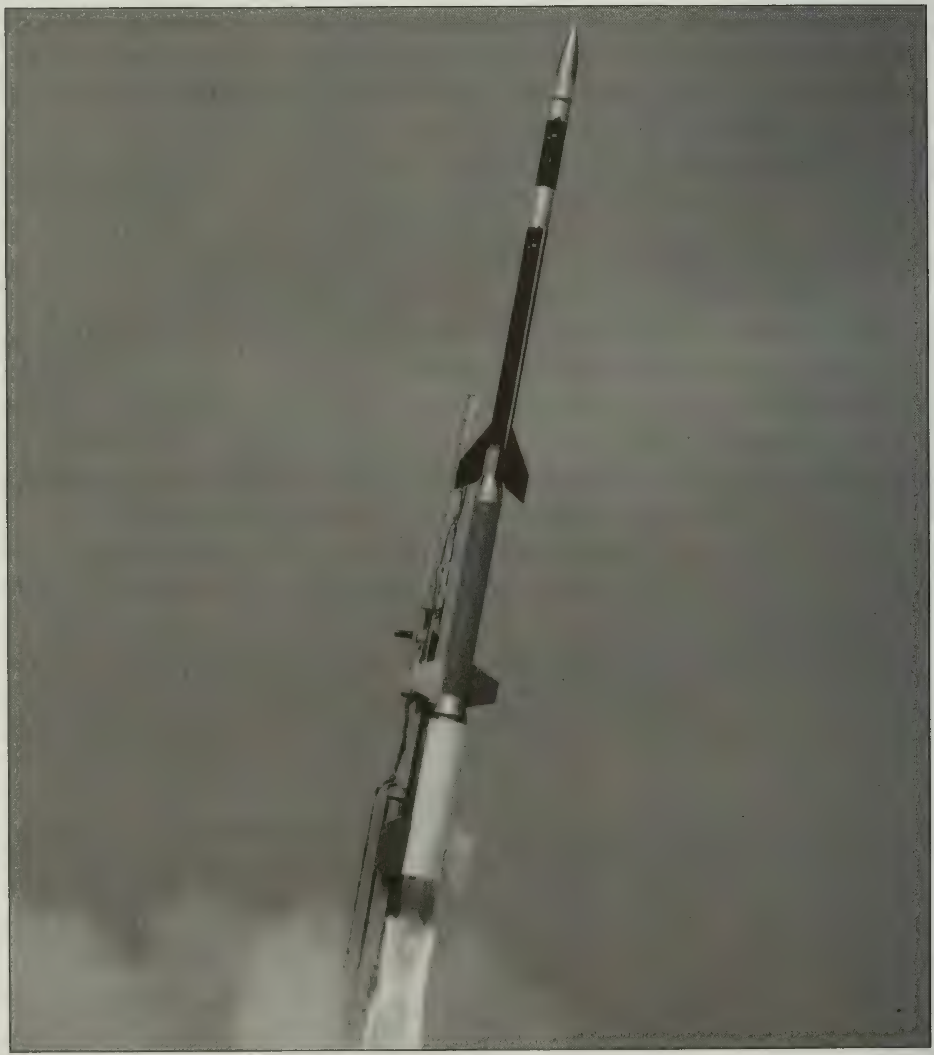

Figure 4–47. The four-stage Black Brant shown here blasting off from a launch pad at the Wallops Island Flight Facility in rural Virginia is at 66 feet (20 meters), the tallest of NASA's 13 sounding rockets. (NASA Photo No. WI-88-589-4)

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[248] *Sounding Rocket Program Handbook*, Document 810-HB-SRP, July 2001, p. 28, *http://www.wff.nasa.gov/code810/docs/SRHB.pdf* (accessed October 25, 2005).

NASA used helium-filled balloons to conduct a variety of scientific studies. Wallops Flight Facility on the eastern shore of Virginia launched an average of 25 scientific balloons each year. Balloons were also launched routinely from the National Scientific Balloon Facility in Palestine, Texas, and the Scientific Balloon Flight Facility in Fort Sumner, New Mexico.

NASA balloons were constructed of thin, 0.002-centimeter (0.8-mil), polyethylene film, about the same thickness as ordinary sandwich wrap. The balloon system included the balloon, parachute, and payload containing the instruments to conduct the experiment, as well as the command and control electronics for the balloon.

Scientific balloons could carry a payload weighing as much as 8,000 pounds (3,630 kilograms), about the weight of three small cars. They could fly to an altitude of 26 miles (42 kilometers), with flights lasting an average of 12 to 24 hours. Some special-purpose, long-duration balloon flights lasted more than two weeks.

The development of an Ultra-Long Duration Balloon (ULDB) expanded the capabilities of the balloon program. The ULDB project developed advanced materials, a superpressure balloon design, and a standard gondola that included power and telemetry/command. The ULDB project also sought to extend flight duration. These advances could be applied to other commercial, DOD, and NASA science balloon missions. Figure 4–48 shows a balloon ready for launch at the National Scientific Balloon Facility in Palestine, Texas.

Table 4–62 lists NASA sounding rocket flights between 1989 and 1998; Table 4–63 lists NASA balloon flights during the same period.

Planetary/Solar System Exploration

NASA's Planetary and Solar System Exploration program encompassed the scientific exploration of the solar system, including the planets and their satellites, comets and asteroids, and the interplanetary medium. The objectives of planetary and solar system exploration missions were the following: 1) determine the nature of planets, comets, and asteroids as a means for understanding the origin and evolution of the solar system; 2) understand Earth better through comparative studies with the other planets; 3) understand how the appearance of life in the solar system related to the chemical history of the solar system; and 4) provide a scientific basis for future use of resources available in near-Earth space.

Magellan

Magellan was the first deep space mission launched by the United States in almost 11 years, and it also was the first launched by the Space Shuttle. Originally scheduled for 1988, NASA remanifested Magellan after the *Challenger* accident and elimination of the Centaur upper stage. The launch took place on May 4, 1989, on STS-30 with an inertial upper stage boosting the spacecraft into a Venus transfer orbit. It arrived at Venus on August 10, 1990, and was inserted into a near-polar elliptical orbit around the planet. Figure 4–49 shows the Earth-to-Venus trajectory.

Figure 4–48. Balloon Ready for Launch at the National Scientific Balloon Facility in Palestine, Texas.

The primary objectives of the Magellan mission were to map the surface of Venus with a synthetic aperture radar (SAR) and to determine the topographic relief of the planet. The Magellan mission scientific objectives were to study land forms and tectonics, impact processes, erosion, deposition, and chemical processes, as well as model the interior of Venus. At the completion of radar mapping, 98 percent of the surface was imaged at resolutions better than 100 meters (328 feet), and many areas were imaged multiple times.

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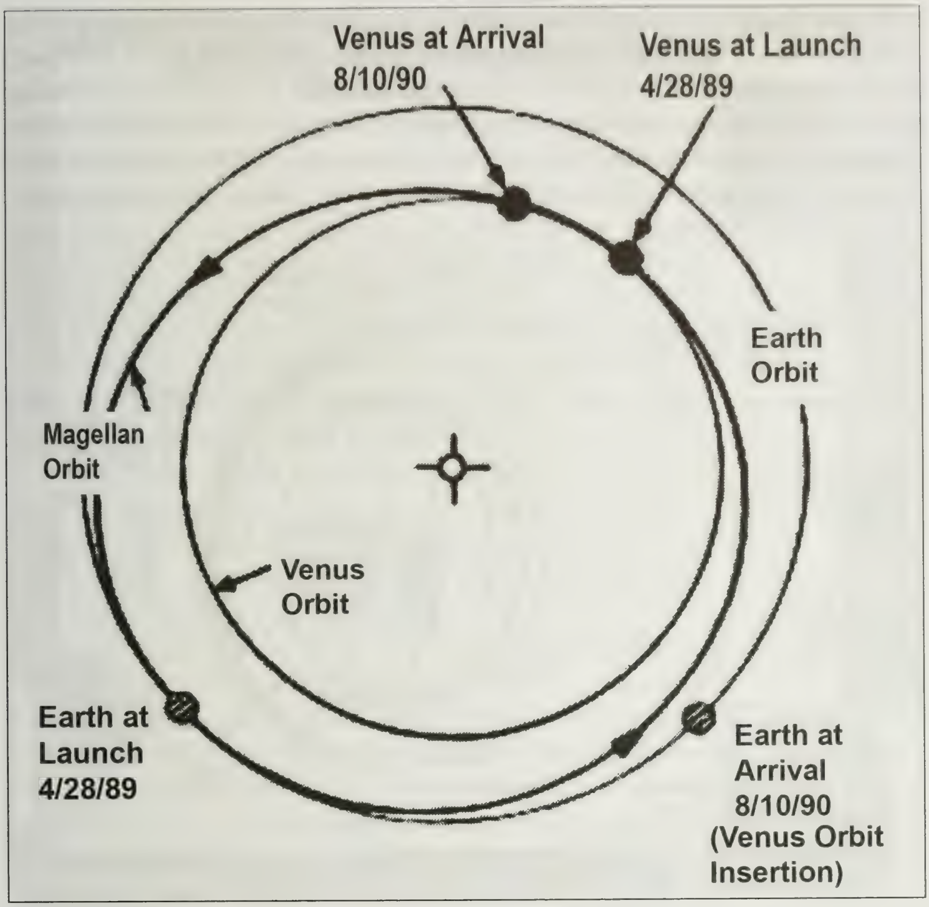
Venus at Arrival
8/10/90
Venus at Launch
4/28/89
Earth
Orbit
Magellan
Orbit
Venus
Orbit
Earth at
Launch
4/28/89
Earth at
Arrival
8/10/90
(Venus Orbit
Insertion)

Figure 4–49. Magellan Earth-to-Venus Trajectory.

A radar system was used for Venus mapping because it could penetrate the thick clouds covering the planet while optical photography could not. Magellan's SAR created high-resolution images by using computer processing on Earth to simulate a large antenna on the spacecraft. The onboard radar system operated as though it had a huge antenna, hundreds of meters long. Its actual diameter was 12 feet (3.7 meters) in diameter.[249] (Real aperture radar can be used to make images, but their resolution is poor.)

Magellan's initial orbit was highly elliptical, taking it as close as 294 kilometers (182 miles) from Venus and as far away as 8,543 kilometers (5,296 miles). The orbit flew over Venus's north and south poles. Magellan completed one orbit every 3 hours, 15 minutes. During the part of its orbit closest to Venus, Magellan's radar mapper imaged a swath of the planet's surface ranging from 17 kilometers to 28 kilometers (10 miles to 17 miles) wide. At the end of each orbit, the spacecraft radioed back to Earth a map of a long ribbon-like strip of the planet's surface captured during that orbit. Venus rotated once every 243 Earth days (about eight months). Each of these periods was called a "cycle." During each cycle, Magellan collected several strips of radar image data while the planet rotated under the spacecraft, eventually covering the entire globe by the end of the 243-day orbital cycle.[250] Figure 4–50 shows Magellan's Venus orbital operations.

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[249] "Space Shuttle Mission STS-30" Press Kit, April 1989, *http://science.ksc.nasa.gov/shuttle/missions/sts-30/sts-30-press-kit.txt* (accessed September 15, 2005).

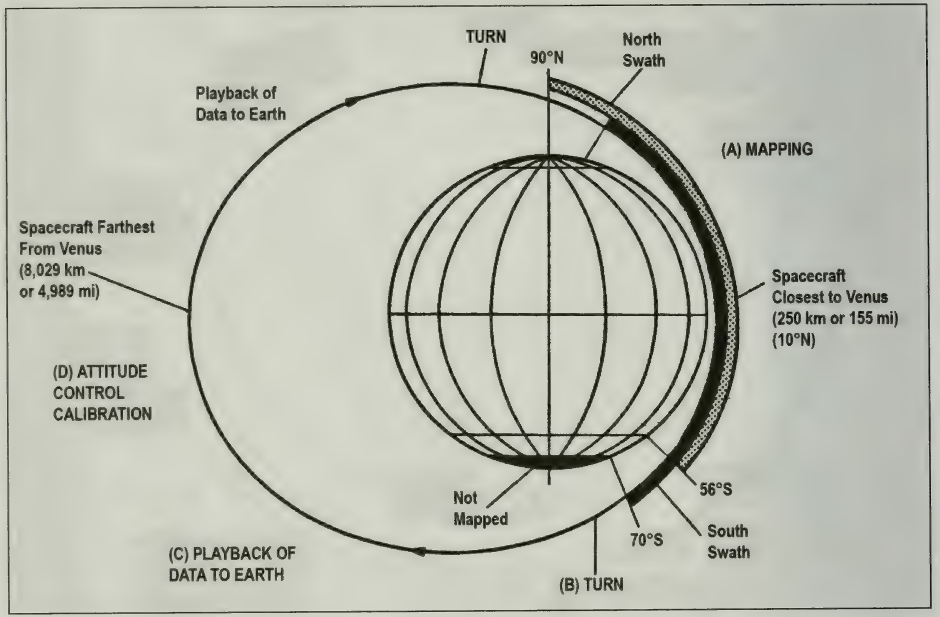
TURN
90°N
North Swath
Playback of Data to Earth
(A) MAPPING
Spacecraft Farthest From Venus (8,029 km or 4,989 mi)
Spacecraft Closest to Venus (250 km or 155 mi) (10°N)
(D) ATTITUDE CONTROL CALIBRATION
56°S
Not Mapped
70°S
South Swath
(C) PLAYBACK OF DATA TO EARTH
(B) TURN

Figure 4–50. Magellan Venus Orbital Operations.

By the end of its first eight-month orbital cycle between September 1990 and May 1991, Magellan had returned to Earth detailed images of 84 percent of Venus's surface. The spacecraft then conducted radar mapping on two more eight-month cycles from May 1991 to January 1992 and from January 1992 to September 1992. This allowed Magellan to capture detailed maps of 98 percent of the planet's surface. The follow-on cycles also allowed scientists to look for any changes in the surface from one year to the next. In addition, because the "look angle" of the radar was slightly different from one cycle to the next, scientists could construct three-dimensional views of Venus's surface.

During Magellan's fourth eight-month orbital cycle at Venus, from September 1992 to May 1993, the spacecraft collected data on the planet's gravity field. During this cycle, Magellan did not use its radar mapper but instead transmitted a constant radio signal to Earth. If it passed over an area of Venus with higher than normal gravity, the spacecraft would slightly speed up in its orbit. This caused the frequency of Magellan's radio signal to change

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[250] "Magellan Summary Sheet," *http://www2.jpl.nasa.gov/magellan/fact1.html* (accessed August 16, 2005).

very slightly due to the Doppler effect. Due to the ability of radio receivers in the NASA/JPL DSN to measure frequencies with very high accuracy, scientists could build a detailed gravity map of Venus.

At the end of Magellan's fourth orbital cycle in May 1993, flight controllers lowered the spacecraft's orbit using a then-untried technique called aerobraking. This maneuver sent Magellan dipping into Venus's atmosphere once every orbit; the atmospheric drag on the spacecraft slowed it and lowered its orbit. When the aerobraking was completed on August 3, 1993, Magellan's orbit reached 180 kilometers (112 miles) from Venus at its nearest point and 541 kilometers (336 miles) at its most distant point. Magellan also circled Venus more quickly, completing an orbit every 94 minutes. This new, more circularized orbit allowed Magellan to collect better gravity data in the higher northern and southern latitudes near Venus's poles.

After the end of the fifth orbital cycle in April 1994, Magellan began a sixth and final orbital cycle, collecting more gravity data and conducting radar and radio science experiments. By the end of the mission in October 1994, Magellan had captured high-resolution gravity data for an estimated 95 percent of the planet's surface.[251]

In September 1994, Magellan's orbit was lowered once more in another test called a "windmill experiment." In this test, the spacecraft's solar panels were turned to a configuration resembling the blades of a windmill, and Magellan's orbit lowered into the thin outer reaches of Venus's dense atmosphere. Flight controllers then measured the amount of torque control required to maintain Magellan's orientation and keep it from spinning. This experiment gave scientists data on the behavior of molecules in Venus's upper atmosphere, and it gave engineers new information useful in designing spacecraft.[252] The mission ended on October 12, 1994 when the spacecraft was commanded to drop lower into the fringes of the Venusian atmosphere during an aerodynamic experiment and, as expected, burned up. Table 4–64 lists major mission events.

The spacecraft consisted of the structure and thermal control, power, attitude control, propulsion, command data and data storage, and telecommunications subsystems. The structure included the high-gain antenna, forward equipment module, spacecraft bus including solar array, and orbit-insertion stage. The high-gain antenna was used as the antenna for the SAR as well as the primary antenna for the telecommunications system to return data to Earth. The parabolic dish was made of strong, lightweight graphite epoxy sheets mounted on an aluminum honeycomb for rigidity. The parabolic dish was a spare from the Voyager project.

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[251] Douglas G. Griffith, Magellan Project Manager (retired), e-mail received September 19, 2005.

[252] "Magellan Mission to Venus," NASA Facts, Jet Propulsion Laboratory, July 1996, updated February 2002, *http://www.jpl.nasa.gov/news/fact_sheets/mgn.pdf* (accessed September 16, 2005).

Magellan's cone-shaped medium-gain antenna received commands and sent engineering data during the 15-month cruise from Earth. A low-gain antenna provided the ground team with an alternative means of commanding the spacecraft in case an emergency prevented use of normal data rates. The altimeter antenna was mounted to one side of the high-gain antenna and pointed vertically down at the surface of Venus during the radar data acquisitions. The forward equipment module contained the radar electronics, the reaction wheels controlling the spacecraft's attitude, and other subsystem components.

The bus was a 10-sided structure. The bus housed the remainder of the subsystem components, including the solar panel array, star scanner, medium-gain antenna, rocket engine modules, command data and data storage subsystem, monopropellant tank, and nitrogen tank for propellant pressurization.

The orbit insertion stage contained a Star 48 solid rocket motor to place the spacecraft into orbit around Venus. Once in orbit, the motor casing was jettisoned. The rocket motor weighed 4,721 pounds (2,141 kilograms), of which 4,430 pounds (2,009 kilograms) were fuel. It had 15,232 pounds (67,755 newtons) of thrust. A combination of louvers, thermal blankets, passive coatings, and heat-dissipating elements controlled the spacecraft's temperature. Normal operating temperature for the spacecraft components ranged between 25°F (-4°C) and 104°F (40°C).

Two solar panels powered the spacecraft and experiments. The array could produce 1,200 watts of power. Two nickel cadmium batteries provided power when the spacecraft was shadowed by the planet, and the batteries allowed normal spacecraft operations independent of solar illumination. The solar arrays charged the batteries.

Electric motors drove the three reaction wheels, which controlled the spacecraft's attitude in relation to the planet and stored momentum while they were spinning. At a point in each orbit near apoapsis, the rocket motors were used to counteract the torque on the spacecraft as the reaction wheels were despun to eliminate excess momentum. There was one reaction wheel for each of the spacecraft's axes—yaw, pitch, and roll. The spacecraft also had 24 thrusters for trajectory correction and attitude control. Figure 4–51 shows a drawing of the spacecraft.

Magellan showed Venus as an Earth-sized planet with no evidence of Earth-like plate tectonics. The landscape was dominated by volcanic features, faults, and impact craters.[253] At least 85 percent of the surface was covered with volcanic flows, the remainder by highly deformed mountain belts. Huge areas of the surface showed evidence of multiple periods of lava flooding with flows lying on top of previous ones. Even with the high surface temperature (475°C) (887°F) and high atmospheric pressure (92 bars), the complete lack of water made erosion a negligibly slow process, and surface features could persist for hundreds of millions of years. Some surface modification in the form of wind streaks was observed. More than 80 percent of Venus lay within 1 kilometer of the mean radius of 6,051.84 kilometers (3,766.7 miles). The mean surface age was estimated to be about 500 million years. A major unanswered question was whether the entire surface had been covered in a series of large events 500 million years ago or if it had been covered slowly over time. The gravity field of Venus was highly correlated with the surface topography, which indicated that the mechanism of topographic support was unlike Earth's, and the topography might be controlled by processes deep in the interior. Details of the global tectonics on Venus remained unresolved.[254] Figure 4–52 shows a section of a Magellan radar image.[255] Figure 4–53 shows a three-dimensional representation of brightness variations in a radar image of Golubkina crater. Table 4–65 provides further mission details.

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[253] "Venus," *http://www1.jsc.nasa.gov/er/seh/venus.html* (accessed May 9, 2006).

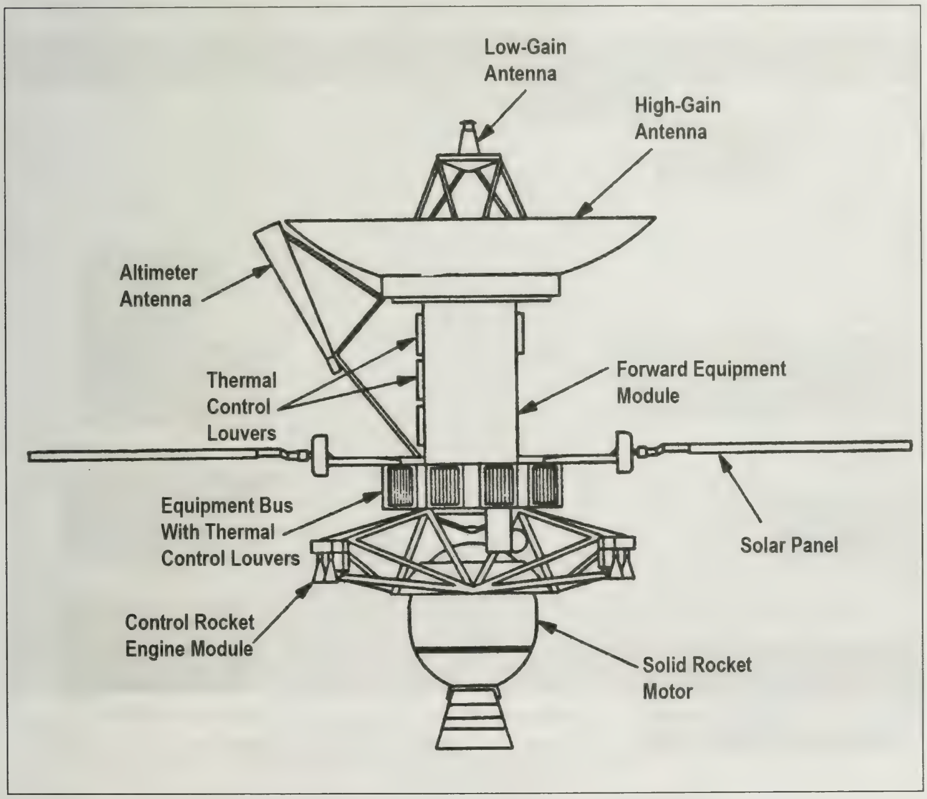
Low-Gain Antenna
High-Gain Antenna
Altimeter Antenna
Thermal Control Louvers
Forward Equipment Module
Equipment Bus With Thermal Control Louvers
Solar Panel
Control Rocket Engine Module
Solid Rocket Motor

Figure 4–51. Magellan Spacecraft.

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[254] "Magellan Mission to Venus," *http://nssdc.gsfc.nasa.gov/planetary/magellan.html* (accessed September 16, 2005).

[255] "Magellan Mission to Venus." Also "Magellan Summary Sheet," *http://www2.jpl.nasa.gov/magellan/fact1.html* (accessed August 16, 2005).

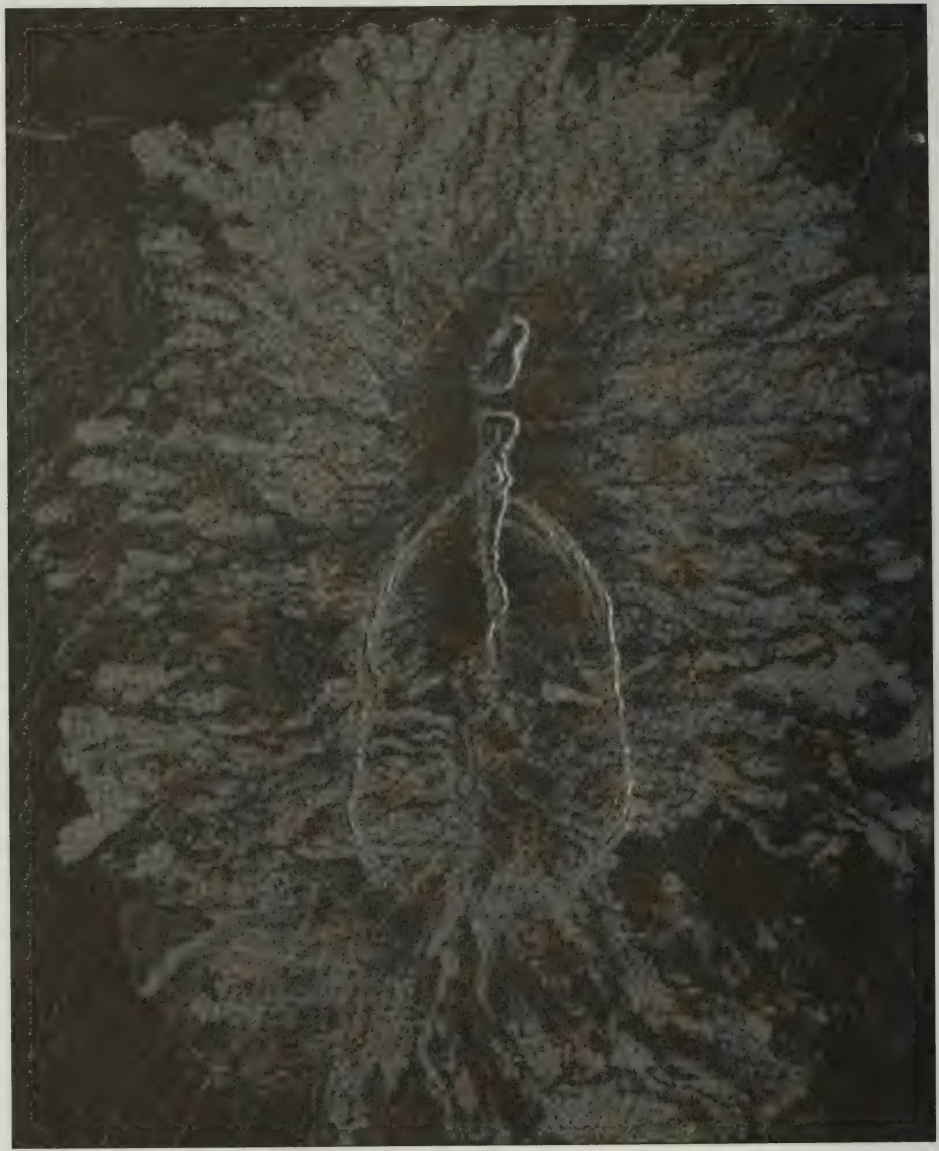

Figure 4–52. Shown is a section of a Magellan radar image of a 40-kilometer by 60-kilometer (25-mile by 37-mile) "petal" type Venusian volcano in eastern Aphrodite Terra. (NSSDC Image Catalog)

Galileo

The Galileo mission, one of NASA's most ambitious deep space exploration projects, used remote sensing by an orbiter and *in situ* measurements by an atmospheric probe to make a comprehensive, long-term study of Jupiter's atmosphere, magnetic field, and moons. Named for the Italian Renaissance scientist Galileo Galilei, who discovered Jupiter's major

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moons in 1610, the mission was the first to use an instrumented probe to make direct measurements in Jupiter's atmosphere and the first to conduct long-term observations of the planet and its magnetosphere and satellites from orbit around Jupiter. The Galileo mission was also the first to encounter an asteroid and photograph an asteroid's moon.

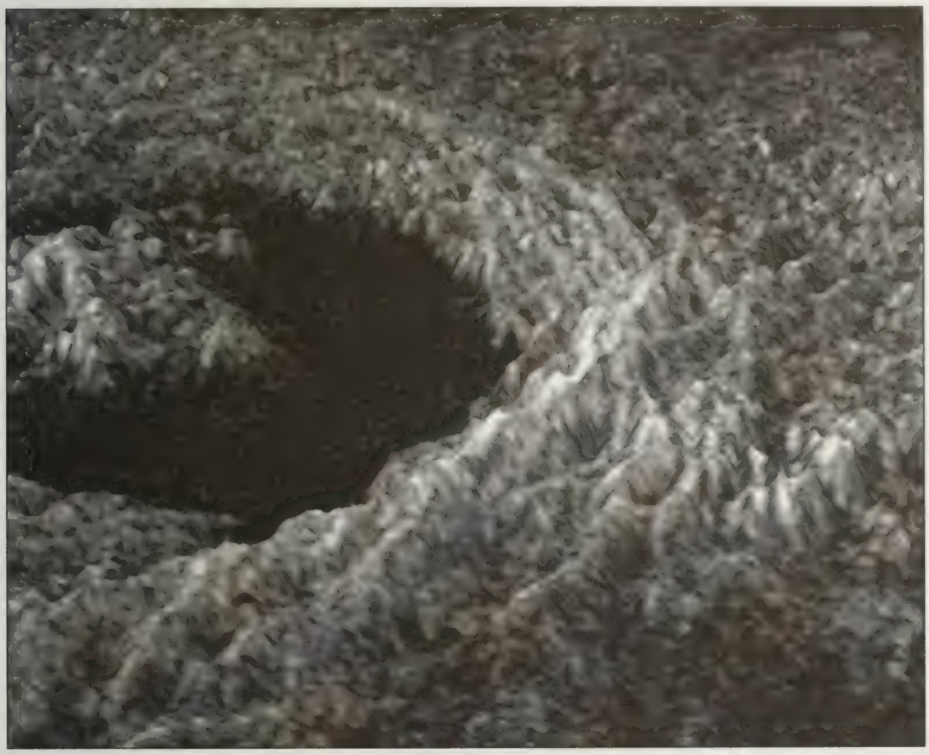

Figure 4–53. This three-dimensional representation of brightness variations in a radar image of Golubkina crater on Venus enhances the structural features of the crater. Golubkina is characterized by terraced inner walls and a central peak typical of large impact craters on Earth, the Moon, and Mars. The terraced inner walls form at late stages in the formation of an impact crater, due to collapse of the initial cavity formed by the meteorite impact. The central peak forms due to rebound of the inner crater floor. (NASA-JPL Photo No. PIA00209)

JPL designed and developed the orbiter spacecraft and operated the mission. Ames Research Center developed the atmospheric probe with Hughes Aircraft Company as prime contractor. The German government was a partner in the mission, providing the spacecraft propulsion subsystem and two science experiments. Scientists from six nations participated in the mission. Galileo communicated with its controllers and scientists through NASA's DSN tracking stations in California, Spain, and Australia.[256]

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[256] "Galileo Overview," *http://www2.jpl.nasa.gov/galileo/overview.html* (accessed September 12, 2005).

The 2,223-kilogram (2.5-ton) Galileo orbiter spacecraft carried 10 scientific instruments; the 339-kilogram (750-pound) probe carried another seven. In addition, the spacecraft radio link to Earth and the probe-to-orbiter radio link served as instruments for other scientific investigations.

Galileo consisted of three segments: the atmospheric probe, a non-spinning (or "despun") section of the orbiter, and the spinning main section of the orbiter. This innovative "dual spin" design allowed part of the orbiter to rotate constantly at 3 revolutions per minute and part of the spacecraft to remain fixed. The orbiter could easily accommodate magnetospheric experiments (which need to take measurements while rapidly sweeping about) while providing stability and a fixed orientation for cameras and other sensors. While the spacecraft flew throught various environments, the spinning section included the fields and particles instruments that sensed and measured the environments directly. The spinning section also held with the main antenna, the power supply, the propulsion module, most of the computers, and control electronics. The despun section carried instruments and other remote sensors whose operation depended on a steady pointing capability. Figure 4–54 shows the spacecraft.

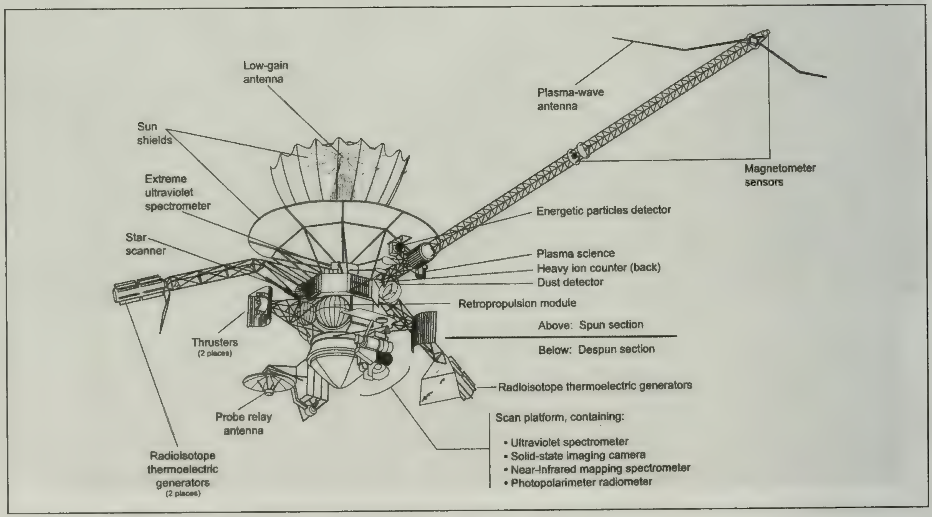
Low-gain antenna
Plasma-wave antenna
Sun shields
Magnetometer sensors
Extreme ultraviolet spectrometer
Energetic particles detector
Star scanner
Plasma science
Heavy ion counter (back)
Dust detector
Retropropulsion module
Above: Spun section
Below: Despun section
Thrusters (2 places)
Radioisotope thermoelectric generators
Probe relay antenna
Scan platform, containing:
• Ultraviolet spectrometer
• Solid-state imaging camera
• Near-infrared mapping spectrometer
• Photopolarimeter radiometer
Radioisotope thermoelectric generators (2 places)

Figure 4–54. Galileo Spacecraft.

Mission Events

Galileo was originally designed for a direct flight to Jupiter of about three and one-half years using a three-stage inertial upper stage booster. When that booster was canceled, plans changed to an early 1985 launch on a Shuttle/Centaur upper stage combination. That was delayed first to 1986 and then to 1989 because of the *Challenger* accident and cancellation of the Centaur upper stage for use with the Shuttle. A two-stage inertial upper stage replaced

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the Centaur, but its lesser capabilities precluded a direct trajectory toward Jupiter. When the Galileo spacecraft was launched on October 18, 1989, on STS-34, the two-stage inertial upper stage boosted it into an unusual Venus-Earth-Earth Gravity Assist (VEEGA) trajectory that would provide the spacecraft with the energy needed to reach Jupiter. In a gravity assist, the spacecraft flies close enough to a planet to be propelled by its gravity, in essence, "stealing" some angular momentum during a flyby of a planet in motion and "removing" momentum from that planet.[257]

The roundabout path required a flight time of a little more than six years. The spacecraft flew past Venus at an altitude of 16,000 kilometers (nearly 10,000 miles) on February 10, 1990. It swung past Earth at an altitude of 960 kilometers (597 miles) on December 8, 1990. That flyby increased Galileo's speed enough to send it on a two-year elliptical orbit around the Sun. The spacecraft made a second Earth swingby exactly two years later on December 8, 1992, at an altitude of 303 kilometers (188 miles) and then headed toward Jupiter. Table 4–66 lists major mission events. Figure 4–55 shows Galileo's trajectory to Jupiter and major events.

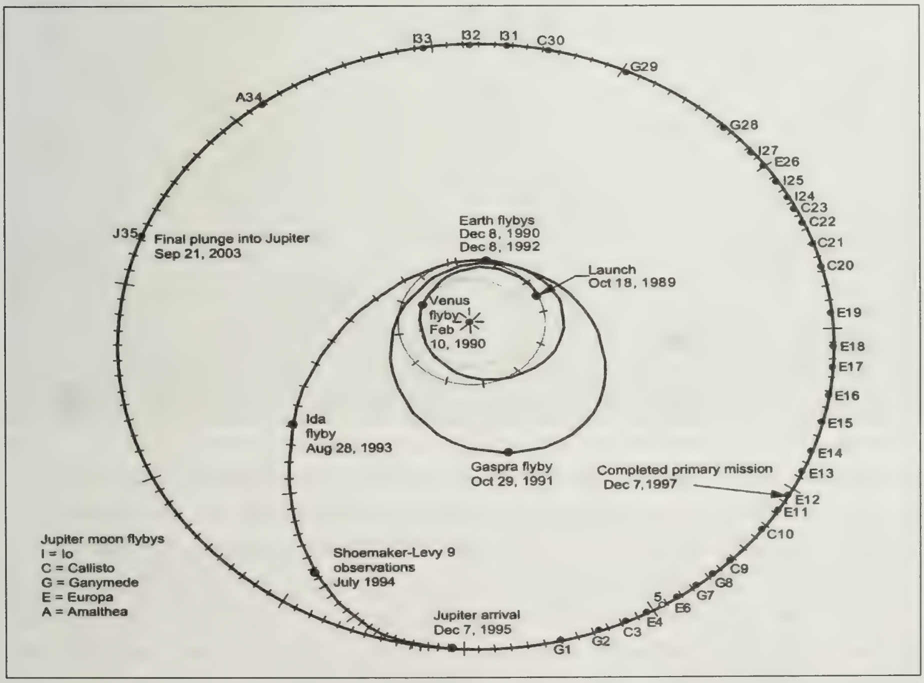
I33
I32
I31
C30
G29
A34
G28
I27
E26
I25
I24
C23
C22
C21
C20
J35
Final plunge into Jupiter
Sep 21, 2003
Earth flybys
Dec 8, 1990
Dec 8, 1992
Launch
Oct 18, 1989
Venus
flyby
Feb
10, 1990
E19
E18
E17
E16
E15
Ida
flyby
Aug 28, 1993
Gaspra flyby
Oct 29, 1991
Completed primary mission
Dec 7,1997
E14
E13
E12
E11
C10
Jupiter moon flybys
I = Io
C = Callisto
G = Ganymede
E = Europa
A = Amalthea
Shoemaker-Levy 9
observations
July 1994
C9
G8
G7
5
E6
E4
C3
G2
G1
Jupiter arrival
Dec 7, 1995

Figure 4–55. Galileo Trajectory.

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[257] Rather than comparing its motion to a slingshot, when a spacecraft uses a gravity assist, the spacecraft comes up and steals some angular momentum during a single flyby of a planet in motion, removing momentum from that planet. A gravity assist is much more like a ping-pong ball hitting the revolving blade of a ceiling fan, taking energy from the fan blade, and bouncing off at a speed greater than it had coming in. "Cassini-Huygens: Mission–Gravity Assists/Flybys, A Quick Gravity Assist Primer," *http://saturn1.jpl.nasa.gov/mission/gravity-assist-primer2.cfm* (accessed September 20, 2005).

The flight path provided opportunities for scientific observations. Scientists obtained the first views of midlevel clouds on Venus and confirmed the presence of lightning on that planet. Scientists also made many Earth observations, mapped the surface of Earth's Moon, and observed its north polar regions.[258]

Because of the trajectory around the Sun, Galileo was exposed to a hotter environment than originally planned. To protect it from the Sun's heat, project engineers devised a set of sunshades and pointed the top of the spacecraft toward the Sun, with the umbrella-like high-gain antenna remaining furled until well after the first Earth flyby in December 1990. Flight controllers communicated with the spacecraft through a pair of low-gain antennae, which sent and received data at a much lower rate.

On April 11, 1991, after Galileo traveled far enough from the heat of the Sun to reduce its exposure to extreme temperatures, the spacecraft executed stored computer commands designed to unfurl the large high-gain antenna. But telemetry received minutes later showed that the motors had stalled, and the antenna had only partially opened. After analyzing Galileo's telemetry and testing on the ground with an identical spare antenna, a team of more than 100 technical experts from JPL and private industry concluded that the problem was most likely due to the sticking of a few antenna ribs. This sticking was caused by friction between their standoff pins and sockets resulting from the loss of lubricant between the parts. The loss of lubricant had been caused by vibrations that the antenna had experienced during several cross-country truck trips between Florida and JPL in California during launch delays.

All attempts to free the stuck hardware failed, including heating and cooling the apparatus by turning it toward and away from the Sun, "hammering" the antenna deployment motors, and spinning the spacecraft at its fastest rotation rate. After efforts lasting more than four years, the project concluded that there was no significant prospect of the antenna being deployed. At the same time, from 1993 to 1996, extensive new flight and ground software was being developed and ground stations of NASA's DSN enhanced to use the spacecraft's low-gain antennae to accomplish the mission. In March 1996, project engineers radioed new software to the spacecraft, inaugurating advanced data compression techniques designed specifically for use with the low-gain antenna. The new software provided programs to "shrink" the voluminous science data that the Galileo orbiter collected and stored on its tape recorder. Software changes, coupled with hardware and software adaptations at ground receiving stations, increased the data rate from Jupiter by as much as 10 times, to 160 bits per second.[259]

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[258] "Galileo End of Mission Press Kit," September 2003, *http://www.jpl.nasa.gov/news/press_kits/galileo-end.pdf* (accessed September 13, 2005).

[259] "Galileo Jupiter Arrival Press Kit," December 1995, *http://www.jpl.nasa.gov/news/press_kits/gllarpk.pdf* (accessed September 12, 2005).

Galileo's two planned visits to the asteroid belt on its way to Jupiter provided opportunities for close observation of these bodies. On October 29, 1991, the spacecraft passed the asteroid Gaspra, flying within 1,601 kilometers (1,000 miles) of its center at a relative speed of about 8 kilometers per second (18,000 miles per hour). The spacecraft obtained the world's first close-up asteroid images, revealing a cratered, complex, irregular body about 20 kilometers by 12 kilometers by 11 kilometers (12.4 miles by 7.4 miles by 6.8 miles) with a thin covering of dust and rubble. Figure 4–56 shows the Gaspra asteroid.

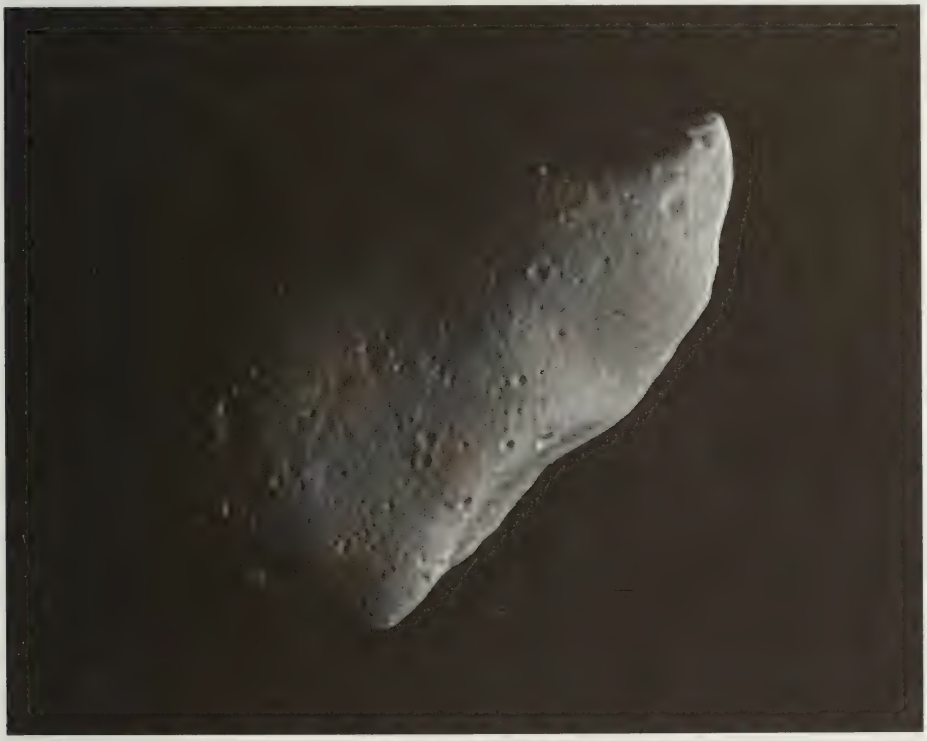

Figure 4–56. This picture of asteroid 951 Gaspra is a mosaic of two images taken by Galileo from 5,300 kilometers (3,300 miles) away some 10 minutes before its closest approach on October 29, 1991. The Sun is shining from the right. A striking feature of Gaspra's surface is the abundance of small craters. More than 600 craters 100 meters to 500 meters (330 feet to 1,650 feet) in diameter are visible. Gaspra's very irregular shape suggests that the asteroid was split from a larger body by nearly catastrophic collisions. (NASA-JPL Photo No. PIA00119)

At the end of August 1993, Galileo flew by a second asteroid, Ida, and discovered the first confirmed asteroid moon. The tiny moon, named Dactyl, had a diameter of only about 1.5 kilometers (less than a mile). Ida was about 55 kilometers (34 miles) long and 24 kilometers (15 miles) wide. Observations indicated that both Ida and Gaspra had magnetic fields. Ida was older than Gaspra, and its surface also was cratered. Figure 4–57 shows Ida and its moon, Dactyl.

In July 1994, Galileo was the only observer in position to obtain images of the far side of Jupiter when more than 20 fragments of comet Shoemaker-Levy plunged into Jupiter's night-side atmosphere during a six-day period. Figure 4–58 shows four images of the comet taken by Galileo.

Arrival at Jupiter

At launch, the spacecraft consisted of an orbiter and a probe. These two elements journeyed together toward Jupiter until July 13, 1995, when the probe was released on a trajectory guiding it into Jupiter's atmosphere. The probe had no engine or thrusters, thus its flight path was established by pointing the Galileo orbiter before the probe's release. Two weeks after the probe was released from the spacecraft on July 27, the orbiter performed the first sustained firing of its main rocket engine while readjusting its flight path toward Jupiter and performing a flyby of Jupiter's volcanic moon Io.[260] On November 26, the orbiter entered Jupiter's environment, crossing over the boundary from interplanetary space into its magnetosphere.[261]

On December 7, 1995, Galileo flew past two of Jupiter's major moons, Europa and Io. Galileo passed Europa at an altitude of about 33,000 kilometers (20,000 miles) and Io at an altitude of about 900 kilometers (600 miles). The same day, Galileo's probe penetrated the top of Jupiter's atmosphere traveling 170,000 kilometers per hour (106,000 miles per hour) while withstanding temperatures twice as hot as the Sun's surface. The probe slowed by aerodynamic braking for about 2 minutes before deploying its parachute and dropping a heat shield. While the orbiter flew 215,000 kilometers (134,000 miles) overhead, the probe floated about 200 kilometers (125 miles) down through the clouds, transmitting data to the orbiter on sunlight and heat flux; pressure; temperature; winds; lightning; and atmospheric composition. The probe sent data from a depth with pressure 23 times that of Earth's average pressure, more than twice the mission requirement. After 58 minutes, the probe succumbed to high temperatures and stopped transmitting.[262] Figure 4–59 illustrates the probe's mission events.

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[260] "Galileo End of Mission Press Kit." Also "Orbiter Deflection Maneuver Status July 27," *http://www2.jpl.nasa.gov/galileo/odm.html* (accessed September 13, 2005).

[261] "Galileo Crosses Boundary into Jupiter's Environment," Jet Propulsion Laboratory Status Report, (December 1, 1995), *http://www2.jpl.nasa.gov/galileo/status951201.html* (accessed September 12, 2005).

[262] "The Galileo Spacecraft," *http://www2.jpl.nasa.gov/galileo/spacecraft.html* (accessed September 12, 2005). Also "Galileo Probe Mission Science Summary," May 10, 1996, *http://spaceprojects.arc.nasa.gov/Space_Projects/galileo_probe/htmls/Science_summary.html* (accessed September 13, 2005).

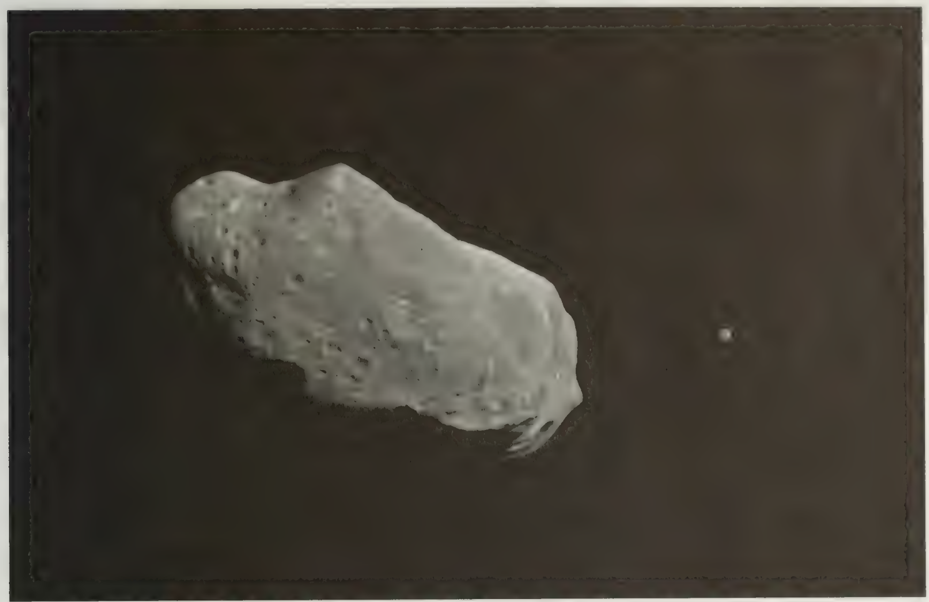

Figure 4–57. This is the first full picture showing both asteroid 243 Ida and its newly discovered moon transmitted to Earth from the Galileo spacecraft—the first conclusive evidence that natural satellites of asteroids exist. Ida, the large object, is about 55 kilometers (34 miles) long. Ida's natural satellite is the small object to the right. This portrait was taken by Galileo's CCD camera on August 28, 1993, about 14 minutes before the spacecraft's closest approach to the asteroid, from a range of 10,870 kilometers (6,755 miles). (NASA-JPL Photo No. PIA00136)

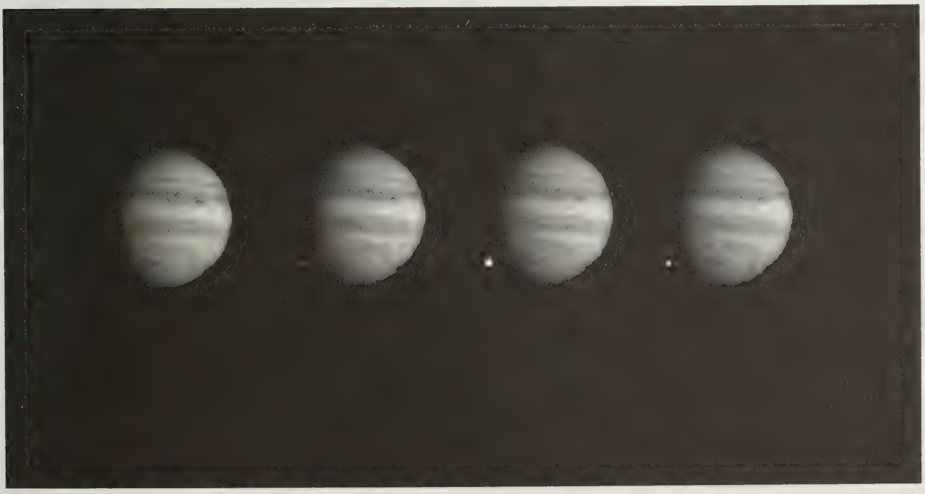

Figure 4–58. These four images of Jupiter and the luminous night-side impact of fragment W of comet Shoemaker-Levy 9 were taken by the Galileo spacecraft on July 22, 1994. The spacecraft was 238 million kilometers (148 million miles) from Jupiter at the time, and 621 million kilometers from Earth. The spacecraft was about 40 degrees from Earth's line of sight to Jupiter, permitting this direct view. (NASA-JPL Photo No. PIA00139)

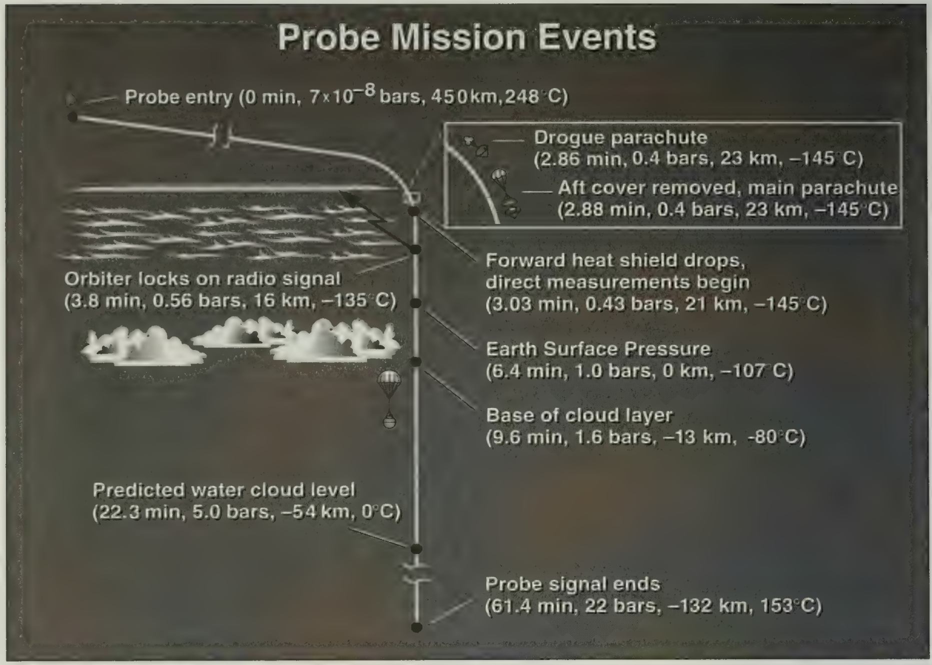
Probe Mission Events
Probe entry (0 min, 7×10⁻⁸ bars, 450km, 248°C)
Drogue parachute (2.86 min, 0.4 bars, 23 km, −145°C)
Aft cover removed, main parachute (2.88 min, 0.4 bars, 23 km, −145°C)
Forward heat shield drops, direct measurements begin (3.03 min, 0.43 bars, 21 km, −145°C)
Orbiter locks on radio signal (3.8 min, 0.56 bars, 16 km, −135°C)
Earth Surface Pressure (6.4 min, 1.0 bars, 0 km, −107°C)
Base of cloud layer (9.6 min, 1.6 bars, −13 km, -80°C)
Predicted water cloud level (22.3 min, 5.0 bars, −54 km, 0°C)
Probe signal ends (61.4 min, 22 bars, −132 km, 153°C)

Figure 4–59. Galileo Probe Mission to Jupiter. (Minutes refer to the amount of time that had passed since the probe entered Jupiter's atmosphere.)[263]

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Probe Science Findings

During its 58 minutes in the Jovian atmosphere, Galileo's probe made several important scientific discoveries. Some of these were very surprising, possibly because the probe entered Jupiter near the edge of a so-called infrared "hot spot." These hot spots were believed to represent regions of diminished clouds on Jupiter to the extent of being among the clearest and driest spots on the planet.

- The Energetic Particle Instrument (EPI) discovered a new, intense radiation belt between Jupiter's ring and the uppermost atmospheric layers while measuring the radiation in the previously unexplored inner regions of Jupiter's magnetosphere. The radiation in this belt measured approximately 10 times as strong as Earth's Van Allen radiation belts and included high-energy helium ions of unknown origin.
- Initial results from Atmosphere Structure Instrument (ASI) measurements of the temperature, pressure, and density structure of Jupiter's atmosphere from the uppermost regions down through an atmospheric pressure of about 24 bars found upper atmospheric densities and temperatures significantly higher than expected.[264] An additional source of heating

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[263] Richard Young, Ames Research Center (e-mail dated September 16, 2005).

[264] An atmospheric pressure of 24 bars is 24 times the atmospheric pressure at sea level on Earth, equal to the pressure at a depth of 230 m (750 ft) in the ocean.

beyond sunlight appeared necessary to account for that result. At deeper levels, the temperatures and pressures were close to expectations. The vertical variation of temperature in the 6-bar to 15-bar pressure range (about 100 kilometers to 150 kilometers below visible clouds) indicated that the deep atmosphere was drier than expected and also was convective. These results suggested the need to reconsider accepted ideas about the abundance and distribution of water on Jupiter.

- The Nephelometer (NEP) instrument, which searched for cloud particles next to the probe, found far less than expected. It did not find thick, dense clouds, and visibility in the atmosphere was much greater than expected in the immediate vicinity of the probe entry site.
- The Net Flux Radiometer (NFR) detected a dense cloud at a far distance away from the probe entry site. Large variations in the brightness of the sky in different directions were noticed until an abrupt drop in the variation below the 0.6-bar pressure level; this indiacted that a cloud layer was most likely the previously postulated ammonia cloud layer, a layer believed to be Jupiter's uppermost cloud layer. The cloud seen by this instrument was not seen by the NEP, leading investigators to conclude the clouds were patchy and the probe went through a relatively clear area.
- Initial results from the Doppler Wind experiment indicated that the winds below the clouds blew at 700 kilometers per hour (435 miles per hour) and were roughly independent of depth. Winds at the cloud tops monitored by the Hubble Space Telescope were of similar strength. These results suggested that winds on Jupiter were probably not produced by heating due to sunlight or condensation of water vapor, two heat sources powering winds on Earth. Rather, a likely mechanism for powering Jovian winds appeared to be heat escaping from the planet's deep interior.
- The Lightning and Radio Emission Detector (LRD) searched for optical flashes and radio waves emitted by lightning discharges. The LRD did not observe optical lightning flashes in the vicinity of the probe but observed many discharges at radio frequencies. The form of the radio signals indicated that the discharges were roughly one Earth diameter away, and the lightning bolts were much stronger than those in Earth's atmosphere. Radio wave intensity suggested that lightning activity was 3 to 10 times less common than on Earth; the intensity also suggested that lightning on Jupiter was very different than on Earth.
- Initial results obtained with the Neutral Mass Spectrometer (NMS) and Helium Abundance Detector (HAD) found several key elements in nearly solar proportions in Jupiter's atmosphere, providing fundamental clues to Jupiter's formation and evolution. The NMS indicated that the atmosphere had much less oxygen—mainly found as water vapor in Jupiter's atmosphere—than the Sun's atmosphere, implying a surprisingly dry atmosphere. The amount of carbon—mainly found as methane gas—was highly enriched with respect to the Sun, while sulfur (in the form of

hydrogen sulfide gas) occurred at greater than solar values. The abundance of neon was highly depleted. Little evidence of organic molecules was found. The HAD very accurately measured the abundance of helium in Jupiter's atmosphere and found the relative abundance of helium approached the level in the Sun's atmosphere.[265]

Galileo's Tour

On December 7, 1995, an hour after receiving the last transmission from the probe 200,000 kilometers (130,000 miles) above the planet, the Galileo spacecraft fired its main engine to brake into orbit around Jupiter, beginning its 23-month, 11-orbit tour of Jupiter's magnetosphere and moons, including 10 close satellite encounters (see Figure 4–60).

The first orbit lasted about seven months. Galileo fired its thrusters at its farthest point in the orbit to keep it the needed distance from Jupiter on later orbits. This adjustment helped reduce the likelihood of damage to spacecraft sensors and computer chips from Jupiter's intense radiation environment. During this orbit, new software was installed, giving the spacecraft additional data processing capabilities needed because of its reliance on its low gain antenna.[266]

During its primary mission orbital tour lasting two years, Galileo made four flybys of Jupiter's moon Ganymede, three of Callisto, and three of Europa. These encounters came about 100 to 1,000 times closer than those performed by NASA's Voyager 1 and 2 spacecraft in 1979. Galileo's instruments scanned and scrutinized the surface and features of each moon. After about a week of intensive observations, when its tape recorder was full of data, the spacecraft spent the period until the next orbital encounter playing back and transmitting the information to Earth.[267] During its two-year primary mission orbital tour, Galileo's orbiter returned 2.4 gigabits of data; the probe returned 3.5 megabits obtained during its 1 hour of operations. In spite of a failed high-gain antenna and some problems with the tape recorder, Galileo accomplished more than 70 percent of its original prime mission science objectives.[268]

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[265] "Galileo Probe Mission Science Summary," May 10, 1996, *http://spaceprojects.arc.nasa.gov/Space_Projects/galileo_probe/htmls/Science_summary.html* (accessed September 13, 2005).

[266] "Galileo End of Mission Press Kit."

[267] "Galileo End of Mission Press Kit."

[268] "The Galileo Mission at Jupiter–Fact Sheet," (no date), *http://www2.jpl.nasa.gov/galileo/Page_1_GEM_Fact_Sheet.pdf* (accessed September 14, 2005).

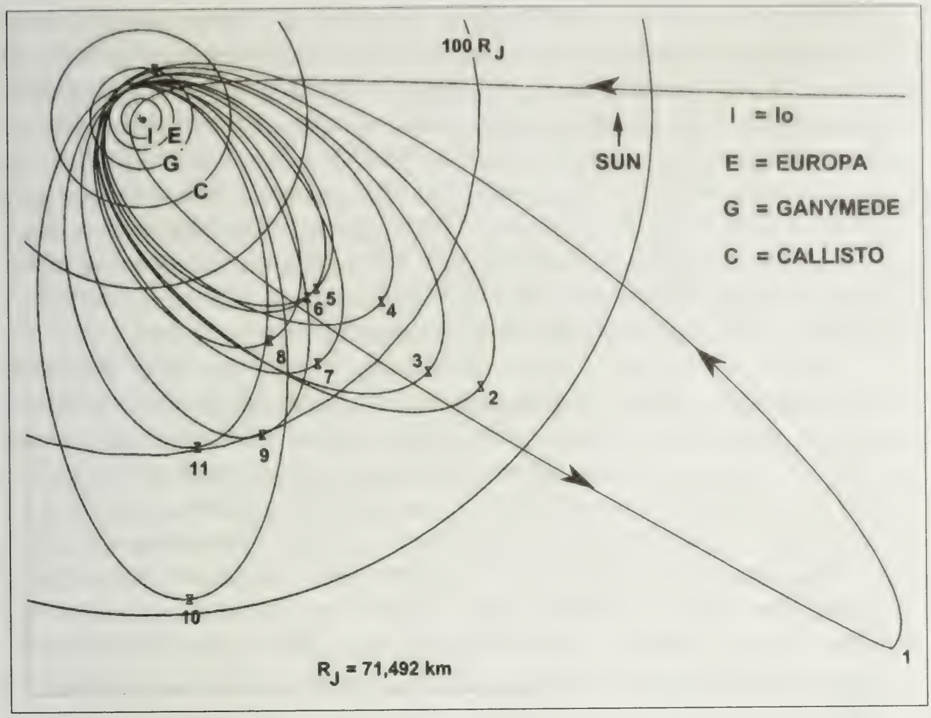

Figure 4–60. This diagram shows the series of 11 flower-shaped orbits on Galileo's primary mission. After the first encounter, the orbits were much shorter, and the time for each ranged from one to two and one-half months

Orbital Tour Science

Galileo's primary mission included a number of key science findings.[269] Some of these findings included the following:

- *Jupiter's Storms and Rings.* Data from the probe's plunge into the top cloud layers of Jupiter and from the orbiter's search for water indicated that Jupiter's billowing thunderstorms were many times larger than those on Earth. These storms resulted from the vertical circulation of water in the top layers, leaving some large areas (such as the probe entry site) where air descended and became dry like the Sahara desert and other areas where water rose to form the thunderstorms. Galileo also found that Jupiter's rings were made of small dust grains that impacts of meteoroids blasted off the surface of Jupiter's four innermost satellites (Adrastea, Metis, Amalthea, and Thebe).
- *Hot, Active Volcanoes on Io.* Voyager 1 first discovered Io's volcanoes in 1979. The volcanoes resulted from 100-meter (328-foot) tides in its

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[269] "Discovery Highlights," Solar System Exploration, Galileo Legacy Site, *http://galileo.jpl.nasa.gov/discovery.cfm* (accessed September 13, 2005). Also "The Galileo Mission at Jupiter–Fact Sheet," *http://www2.jpl.nasa.gov/galileo/Page_1_GEM_Fact_Sheet.pdf.*

solid surface. Galileo found evidence of very hot volcanic activity on Io and observed dramatic changes compared to observations during Voyager and even during the period of Galileo's observations. By taking Io's temperature with Galileo's instruments, scientists learned that some of Io's volcanoes were hotter (1,800°C [3,240°F]) than Earth's. From this, scientists surmised that lava made of a silicate material rich in magnesium erupted from below Io's surface. Galileo also spotted changes more than 100,000 square miles (~260,000 square kilometers) in size on Io's surface that occurred within the past five months due to coating by volcanic debris as well as longer-term changes since the Voyager flybys.

- *A Possible Ocean on Europa.* Possessing more water than the total amount found on Earth, Europa appeared to have had, in recent geologic history, a salty ocean underneath its icy cracked and frozen surface, as revealed in images from Galileo with resolutions as small as 26 meters (85 feet). Ice "rafts" up to 15 kilometers (9.3 miles) across appeared to have broken and drifted apart; a frozen "puddle" smoothed over older cracks; warmer material bubbled up from below to blister the surface; evaporative-type salts were exposed; and a lack of craters showed the surface to be relatively young. Heat to melt the ice below could have come from Europa's exposure to tidal friction from the gravity of Jupiter—less severe but as significant as the similar effect on Io.
- *Ganymede's Magnetic Field.* The magnetic field discovered on Ganymede was the first found on a moon. Scientists suggested that enough heat from internal tidal friction, perhaps arising from a slightly different orbit in its past, caused the separation of material inside Ganymede and the "stirring" of a molten core of iron or iron sulfide, generating Ganymede's magnetic field. Ganymede's magnetic field was found to be larger than the magnetic field on the planet Mercury.
- *Evidence for an Ocean Hidden Beneath Callisto's Surface.* Galileo discovered evidence supporting the existence of a subsurface ocean on Callisto. The ocean would have had to be deep enough inside the moon that it did not affect the moon's heavily cratered surface. Instead, the ocean might be "showing itself" indirectly through the magnetic field it generated. An electric flow in a salty ocean might be generated by Jupiter's strong magnetic field passing through it. Galileo also discovered an atmosphere of hydrogen and carbon dioxide on Callisto.[270]

Extended Europa Mission

The GEM was a two-year, 14-orbit, low-cost extension of Galileo's exploration of the Jovian system beginning in December 1997. The longest part of this campaign, consisting of eight orbits around Europa, lasted through

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[270] "Galileo Mission Continues To Soar," The Planetary Society, *http://www.planetary.org/html/news/articlearchive/headlines/1997/headln-121997.html* (accessed September 13, 2005).

May 4, 1999. The GEM objectives were to study and characterize Europa's crust; atmosphere; and possible ocean, past or present, beneath Europa's icy surface using imaging, gravity, and space physics data.[271] Galileo made its closest approach to Europa on December 16, 1997 at 201 kilometers (125 miles). Mission data was compared with previous images for surface changes that might have occurred, and the surface was scanned for signs of spewing active ice volcanoes and other direct evidence. Because a flowing, salty subsurface ocean could generate a magnetic field, scientists tried to determine if the magnetic signals nearest Europa were generated from within. By measuring the pull of Europa's gravity, the thickness of the ice shelf could be better determined.

Four Callisto encounters between May 5 and October 10, 1999, rapidly lowered the spacecraft's orbit to Io for the third part of the extended mission. Called the Jupiter water/Io torus study, its 10 orbits around Io focused on detailed storm and wind patterns in Jupiter's atmosphere, including thunderstorms, and mapped the distribution of water. Galileo mapped the density of the Io torus, a donut-shaped cloud of charged particles that rings Io's orbit, and used the gravitational pull of Callisto to halve the orbit's perijove (closest distance to Jupiter) to prepare for encountering Io. Scientists also looked at Callisto's magnetic field signatures to search for further evidence of an ocean.[272]

The Io campaign from October 11, 1999, through December 31, 1999, consisted of two orbits around Io.[273] The campaign obtained high-resolution images and a compositional map of Io. The campaign also sampled a volcanic plume, flying 500 kilometers (310 miles) over the active volcano Pillan Patera. Table 4–67 lists all of Galileo's encounters, both the primary and the extended mission through 1999. See Table 4–68 for additional mission details.

The Discovery Program

In 1989, NASA's Solar System Exploration Division initiated a series of workshops to define a new strategy for exploration through the year 2000. The panels included a Small Mission Program Group chartered to devise a rationale for missions that would be low cost and allow focused scientific questions to be addressed in a relatively short time. The group recommended the use of small spacecraft to implement limited-scope missions. This was different from NASA's usual way of conducting very large missions carrying many instruments. These large missions usually took many years to organize and often cost more than one billion dollars.

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[271] "Galileo Europa Mission (GEM) Fact Sheet," (no date), *http://www2.jpl.nasa.gov/galileo/gem/fact.html* (accessed August 18, 2005).

[272] "The Galileo Europa Mission–Exploring Through 1999," The Galileo Mission at Jupiter–Fact Sheet, *http://www2.jpl.nasa.gov/galileo/Page_2_GEM_Fact_Sheet.pdf* (accessed September 14, 2005).

[273] "The Galileo Europa Mission–Exploring Through 1999," The Galileo Mission at Jupiter–Fact Sheet.

Although the proposal was initially greeted with skepticism, largely because of the example set by the low-cost Planetary Observer program and the Mars Observer mission, which "grossly overran" its budget and schedule, they agreed to use the successful Explorers Program as a model.[274] The group gave this new program the name "Discovery." A Science Working Group was established and in 1990; the group reviewed a number of concepts that could be implemented as less costly missions. In May 1991, after examining specific missions and the feasibility of the Discovery approach, Wesley Huntress, Director of the Solar System Exploration Division, decided to include the Discovery Program as an element in the division's 1991 Strategic Plan. The NEAR was planned as the first Discovery mission.[275]

Meanwhile, in the fall of 1991, the Senate Appropriations Committee directed NASA in the FY 1992 appropriations bill to prepare a plan "to stimulate and develop small planetary or other space science projects, emphasizing those which could be accomplished by the academic or research communities." NASA described the Discovery initiative[276] in the requested report submitted to Congress in April 1992.

The Discovery Program was a good fit with NASA Administrator Goldin's "faster, better, cheaper" approach to space science missions. Discovery missions aimed to incorporate state-of-the-art technologies into smaller projects with faster turnaround to foster the continuing conduct of science at significantly lower cost.

Discovery missions had a $150 million ceiling for development; operations costs could not exceed $35 million; and mission development from start through launch plus 30 days could take no more than 36 months. Spacecraft had to fit on an ELV no larger than a Delta II. Anyone could submit proposals—academia, industry, and the government—and the formation of teams was encouraged.[277] NASA did not specify development details of Discovery missions. Rather, each science team had maximum flexibility to pursue innovative and cost-effective approaches to meet mission goals. The Discovery Program "bought" the mission from the Principal Investigator who was accountable for the scientific success of the mission. This manage-

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[274] "A Look Back at the Beginning: How the Discovery Program and the NEAR Mission Came To Be," *Discovery Dispatch*, 2 (January 2001): 1–2, *http://discovery.nasa.gov/news/newsletters/newsletter_archive/2001/January2001.pdf* or *http://discoverynewfrontiers.msfc.nasa.gov/lib/presentations/docs/HistoricalDiscoveryProgramInformation.doc* (accessed October 25, 2005).

[275] "A Look Back at the Beginning: How the Discovery Program and the NEAR Mission Came To Be," *Discovery Dispatch*, 2 (January 2001): 1–2.

[276] "National Aeronautics and Space Administration, Small Planetary Mission Plan, Report to Congress, April 1992," in Logsdon, ed. *Exploring the Unknown, Vol. V.*, pp. 461–468.

[277] Costs given in FY 1992 dollars. Howard E. McCurdy, *Faster Better Cheaper: Low-Cost Innovation in the U.S. Space Program* (Baltimore, MD: The Johns Hopkins University Press, 2001), pp. 55–56. In FY 1999 dollars, ceilings were listed as $190 million for design and development through launch and total mission cost at $299 million, including preliminary analysis, definition, launch services, and mission operations, *The Near Earth Asteroid Rendezvous: A Guide to the Mission, the Spacecraft, and the People* (1999), p. 20 (NASA History Office Folder 17070).

ment approach ensured performance-based missions emphasizing delivery of scientific data. The programmatic goals of Discovery missions were to do the following:[278]

- Create a new way of doing business between a government agency and the private sector.
- Demonstrate that the philosophy of "faster, better, cheaper" could successfully yield a rapid development, very inexpensive planetary science mission with significant responsibility vested with the Principle Investigator.
- Create an innovative education and outreach program that stimulates public interest in planetary exploration.

NEAR and Mars Pathfinder were the first projects selected under the program. Work on the two began in 1993. The Lunar Prospector, the third mission and first selected competitively, began in 1995. Stardust was the fourth Discovery mission, launched in 1999. The Comet Nucleus Tour (CONTOUR) and Genesis missions were selected in 1997. Table 4–69 lists NASA-approved Discovery missions selected through 1998.

Near Earth Asteroid Rendezvous

The primary goal of the NEAR mission was to rendezvous with the asteroid 433 Eros (an S-class asteroid) approximately 355 million kilometers (220 million miles) from Earth and gather data on its composition and physical properties (mineralogy, morphology, internal mass distribution, and magnetic field). The NEAR was the first mission to put a spacecraft in orbit around an asteroid and the first to orbit a body whose mass and exact size were unknown until arrival. Since Discovery missions were limited to launch vehicles no larger than a Delta II, the NEAR mission used a "long, looping path" to the asteroid belt and back toward Earth and depended on a gravity assist from Earth to reach Eros. The spacecraft's retrograde orbit, moving opposite the asteroid's rotation, enabled its stable orbit.[279]

Work on the project began in 1993. The Johns Hopkins University Applied Physics Laboratory (APL) was responsible for mission operations, which were conducted through a dedicated NEAR Mission Operations System Ground Segment at the APL. JPL was responsible for navigation. Science operations were conducted from the Science Data Center at the APL. All data from the spacecraft were forwarded to the Science Data Center for processing, distribution, and archiving.

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[278] "Lunar Prospector: End of Mission and Overview," Press Kit, July 1999, *http://lunar.arc.nasa.gov/resources/LPBckgrn.pdf* (accessed October 25, 2005).

[279] Scott L. Murchie et al, "NEAR So Far: Approaching Asteroid Eros," *The Planetary Report* (November/December 1998): 4-8.

The journey to Eros took four years. A year after its launch, on February 18, 1997, the NEAR spacecraft established a record for the greatest distance from the Sun for a solar-powered spacecraft when it reached 327 million kilometers (203 million miles). On June 27, 1997, the NEAR spacecraft performed a 25-minute flyby of the asteroid 253 Mathilde, flying 1,212 kilometers (753 miles) above the asteroid and photographing 60 percent of the asteroid's surface. This was the first look at a C asteroid. The collected information indicated that craters covered the 4.5-billion-year-old asteroid and that it was less dense than previously believed.

A midcourse correction on July 3, 1997, sent the NEAR spacecraft past Earth on January 23, 1998 for a gravity assist on its way to Eros; the spacecraft flew about 540 kilometers (335 miles) above Ahvaz in southwestern Iran. Viewers on the ground in France, the southern United States, and Hawaii reported seeing the spacecraft as it approached. On April 1, 1998, the NEAR spacecraft set a record as the most distant manufactured object detected by optical means when an amateur astronomer in New South Wales, Australia, spotted the spacecraft at a distance of 33.65 million kilometers (20.91 million miles) from Earth.

A series of engine burns in December were required for the spacecraft to catch up with and orbit around the faster-moving asteroid. However, on December 20, 1998, the first rendezvous burn was aborted and contact with the spacecraft was lost for 27 hours.[280] The aborted engine burn resulted in a postponement of the NEAR spacecraft's orbit of Eros, which had been scheduled for January 10, 1999. Instead, the NEAR spacecraft was put on a backup trajectory allowing a different flyby than originally planned. As part of this new plan, the spacecraft flew past Eros on December 23, 1998, at a range of 3,827 kilometers (2,378 miles) (distance measured from the center of mass), observing about 60 percent of the asteroid. During its flyby, the NEAR spacecraft discovered that Eros was smaller than expected, and it had two medium-sized craters, a long surface ridge, and a density similar to the density of Earth's crust.[281] Following the flyby, the NEAR spacecraft conducted a successful 24-minute, large bipropellant engine burn on January 3, 1999, to increase the spacecraft's speed for rendezvous with Eros, rescheduled for February 2000. A small hydrazine engine burn on January 20 "fine-tuned" the spacecraft's trajectory and increased its speed by 14 meters per second (31 miles per hour). Periodic trajectory burns throughout the year set the NEAR spacecraft on course to begin orbiting the asteroid on February 14, 2000. The spacecraft landed on Eros on February 12, 2001.[282] In March 2000, the spacecraft was

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[280] It was determined that the abort had been caused when the brief engine burn exceeded certain safety limits associated with the on-board system autonomously controlling the spacecraft. Reprogramming of the values was done, readying the spacecraft for a January 3, 1999 main engine burn.

[281] Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, pp. 161–162.

[282] "NEAR Spacecraft To Fly by Asteroid Eros on December 23; Rendezvous with Eros in 2000," The Johns Hopkins University Applied Physics Lab News Archive, December 22, 1998, *http://near.jhuapl.edu/news/flash/98dec22_3.html*, "NEAR Spacecraft Makes Planned Flyby of Asteroid Eros," December 23, 1998, *http://near.jhuapl.edu/news/flash/98dec23_1.html*, "NEAR Spacecraft Set for Jan. 3 Main Engine Burn," December 30, 1998, *http://near.jhuapl.edu/news/flash/98dec30_1.html*, and Helen Worth, "NEAR Team Recovers Mission After Faulty Engine Burn," January 29, 1999, *http://near.jhuapl.edu/news/articles/99jan29_1/* (all accessed August 8, 2005).

renamed NEAR Shoemaker to honor Dr. Eugene M. Shoemaker, the geologist who influenced decades of research on the role of asteroids and comets in shaping the planets. Dr. Shoemaker co-discovered comet Shoemaker-Levy 9; the comet crashed into Jupiter in 1994.

The NEAR spacecraft comprised two independent structures: the propulsion system and the spacecraft. The APL designed and fabricated the spacecraft structure. Aerojet, the propulsion system vendor, built the propulsion system structure. These systems were coupled at the aft deck. The spacecraft structure was composed of the spacecraft adapter, two decks, and eight side panels.[283]

The three major components—instruments, solar panels, and high-gain antenna—were fixed and body-mounted. The system was designed to be highly fault-tolerant. Fully redundant subsystems included the complete telecommunication system (except the high-gain and medium-gain antennae), the solid-state recorders, command and telemetry processors, data buses, attitude interface unit and flight computers for guidance and control, and power subsystem electronics. The use of redundant components provided additional fault tolerance. The NEAR spacecraft had 2 inertial measurement units (1 operational and 1 backup), 5 sun sensors, and 11 small thrusters.

The NEAR spacecraft design was mechanically simple and geared toward a short development and test time. The solar panels, the high gain antenna (HGA), and the instruments were all fixed. The 1.5-meter (4.9-foot) antenna and four solar panels were mounted on the outside of the forward deck. The solar panels were folded down along the spacecraft sides during launch and were deployed shortly after separation from the launch vehicle. Most electronics were mounted on the forward and aft decks. The science instruments, except for the magnetometer, were hard-mounted on the outside of the aft deck with co-aligned fields-of-view. The magnetometer was mounted on the HGA feed. The interior of the spacecraft contained the propulsion module.[284]

The NEAR spacecraft was the first probe to rely on solar cells for power during operations beyond the Mars orbit—a technical innovation in spacecraft design. It had a design lifetime of four years and the capability to operate at distances of 203 million miles (327 million kilometers) from the Sun. Other technical innovations included the following:

- The first spaceflight of a laser incorporating an inflight calibration system.
- The first spaceflight using a near-infrared system with a radiometric calibration target and an indium-gallium-arsenide focal plane array that did not require cooling with liquid nitrogen.
- The first spaceflight of a silicon solid-state detector viewing the Sun and measuring the solar input x-ray spectrum at high resolution.

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[283] A. G. Santo, S. C. Lee, and R. E. Gold, "NEAR Spacecraft and Instrumentation," pp. 1–2, *http://near.jhuapl.edu/PDF/SC_Inst.pdf* (accessed August 10, 2005).

[284] A. G. Santo, S. C. Lee, and R. E. Gold, "NEAR Spacecraft and Instrumentation," p. 1.

- The first spaceflight of a bismuth germanate anti-coincidence shielded gamma-ray detector.[285]

Table 4–70 provides further NEAR mission details.

Lunar Prospector

The Lunar Prospector was launched from Cape Canaveral, Florida, on January 6, 1998, on top of a solid-fueled Athena II launch vehicle on a one-year mission to map the entire lunar surface. The spacecraft successfully collected data about the chemical composition of the lunar surface, the gravity and magnetic fields, and the resources of the Moon. It was the first launch of the Athena II ELV, the third mission to launch in NASA's Discovery Program, and the first competitively selected Discovery mission. The mission successfully demonstrated NASA's "faster, better, cheaper" concept and was one of the most cost-effective planetary missions ever flown, costing approximately $63 million.[286]

After traveling 105 hours, the spacecraft entered orbit around the Moon on January 11, 1998, following a series of orbit burns. It reached its mapping orbit on January 13 and settled into its final orbit within a few more days. (See figure 4–61 for the mission profile). On December 19, 1998, the spacecraft was placed into an orbit with an average altitude of 40 kilometers (25 miles). This transition orbit was between the nominal mapping orbit (with altitude of 100 kilometers) (62 miles) and the extended mission orbit (with altitude of 25 kilometers to 30 kilometers) (16 miles to 18 miles), where the gravity model was verified. On January 28, 1999, the spacecraft was successfully maneuvered into its extended mission orbit. Two burn sequences placed the spacecraft in a 15-kilometer by 45-kilometer (9-mile by 28-mile) altitude orbit to maintain an average altitude above the surface of 30 kilometers (18 miles). It was the lowest altitude mapping of another world.

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[285] "The Near Earth Asteroid Rendezvous; A Guide to the Mission, the Spacecraft, and the People," The Johns Hopkins University Applied Physics Laboratory, December 1999, p. 15, *http://near.jhuapl.edu/media/99-1030B_NEARMarch.pdf* (accessed August 8, 2005).

[286] Howard McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program*, p. 5. Also "Lunar Prospector, End of Mission & Overview," Press Kit, July 1999, pp. 5, 7–8, *http://lunar.arc.nasa.gov/resources/LPBckgrn.pdf* (accessed August 2, 2005).

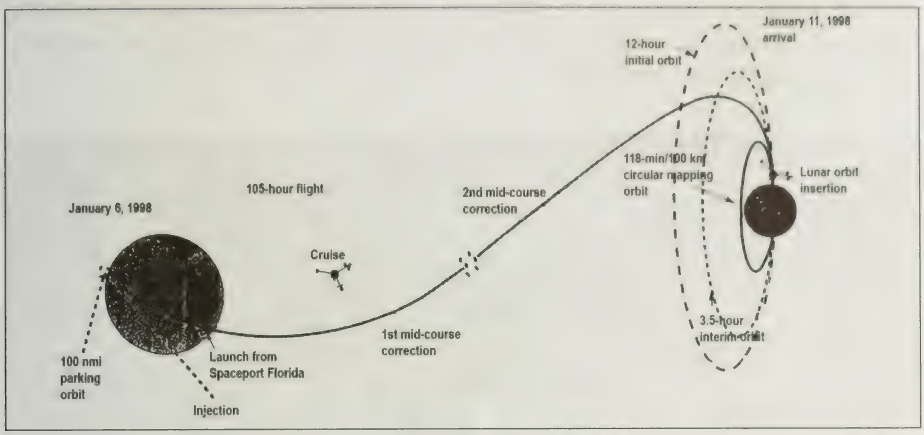
January 11, 1998
arrival
12-hour
initial orbit
118-min/100 km
circular mapping
orbit
Lunar orbit
insertion
January 6, 1998
105-hour flight
2nd mid-course
correction
Cruise
1st mid-course
correction
3.5-hour
interim orbit
100 nmi
parking
orbit
Launch from
Spaceport Florida
Injection

Figure 4–61. Lunar Prospector Mission Profile.

On March 5, 1998, the Prospector science team announced the discovery of a "definitive signal" for water ice at both the lunar poles, the first such discovery. A conservative analysis of the available data indicated that a significant quantity of water ice, possibly as much as 300 million metric tons (661,387 pounds), was mixed into the lunar soil at each pole, with 15 percent more at the north pole than at the south pole. The presence of water ice at both lunar poles was strongly indicated by data from the spacecraft's neutron spectrometer instrument. That quantity was dispersed over an area of 3,600 square miles to 18,000 square miles (9,324 square kilometers to 46,620 square kilometers) across the northern pole and an additional area of 1,800 square miles to 7,200 square miles (4,662 square kilometers to 18,648 square kilometers) across the southern polar region.[287] Scientists also detected strong, localized magnetic fields; delineated new mass concentrations on the surface; and mapped the global distribution of major rock types, key resources, and trace elements. There were strong suggestions that the Moon had a small, iron-rich core.[288]

On July 31, 1999, the Lunar Prospector was targeted to impact in a permanently shadowed area of a crater near the lunar south pole. It was hoped that the impact would liberate water vapor from the suspected ice deposits in the crater and that the plume would be detectable from Earth; however, no plume was observed. The lack of physical evidence left open the question of whether ancient comet impacts delivered ice that remained buried in permanently shadowed regions of the Moon, as suggested by the large amounts of hydrogen measured indirectly by the spacecraft during its main mapping mission.[289] Figure 4–62 depicts the Lunar Prospector before it impacted the Moon's surface.

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[287] "Lunar Prospector Finds Evidence of Lunar Ice," *HQ Bulletin* (March 23, 1998): 3 (History Office Folder 5728).

[288] "NASA's Lunar Prospector Sends Back a Wealth of Scientific Data," *HQ Bulletin* (September 14, 1998): 1 (History Office Folder 16834).

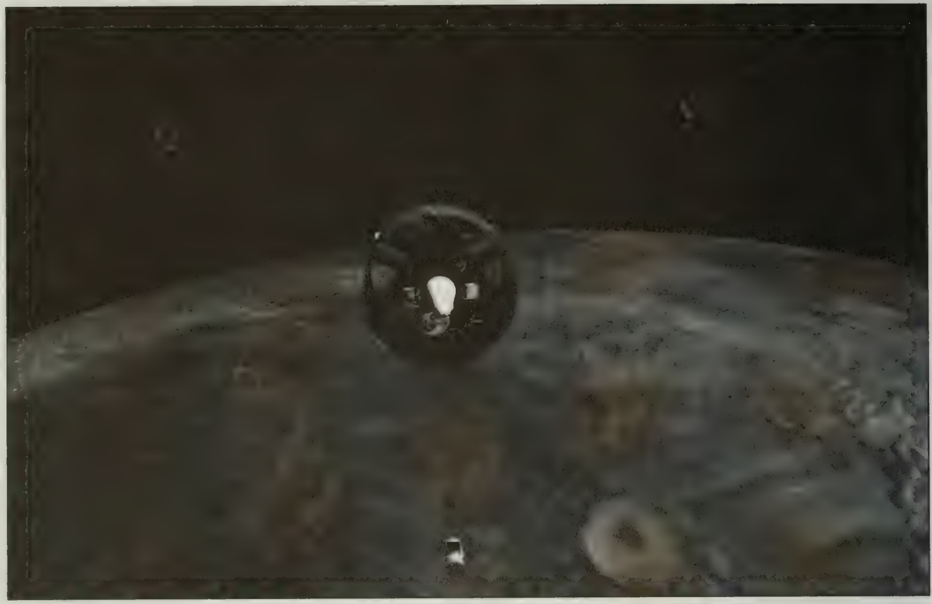

Figure 4–62. This image is an artist's conception of the front of the Lunar Prospector spacecraft just before it impacts the Moon. It was released July 29, 1999, two days before the actual impact. (Ames Research Center Home Page)

The Lunar Prospector was a graphite-epoxy drum with three radial instrument booms, spin-stabilized and controlled by six hydrazine monopropellant 22-newton thrusters. Communications were through two S-band transponders and a slotted, phased-array medium-gain antenna and omnidirectional low-gain antenna. There was no on-board computer; ground command was through a 3.6-kbps telemetry link commanding a single on-board command and data handling unit. Data was downlinked directly and also stored on a solid-state recorder and downlinked after 53 minutes to ensure all data collected during communications blackout periods was received. See Table 4–71 for further details.

Clementine

NASA and the Ballistic Missile Defense Organization, formerly the Strategic Defense Initiative Organization (SDIAO), jointly sponsored the Clementine project.[290] It was also known as the Deep Space Probe Science

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[289] "No Water Ice Detected From Lunar Prospector Impact," *NASA News* Release 99-119, October 13, 1999, *http://nssdc.gsfc.nasa.gov/planetary/text/lp_pr_19991013.txt* (accessed August 2, 2005).

[290] "Clementine," NSSDC Master Catalog, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1994-004A* (accessed April 24, 2006).

Experiment (DSPSE). Clementine was the DOD equivalent of a NASA "faster, cheaper, better" Discovery Program mission, built over a relatively short two-year development cycle and at a lower cost than more elaborate missions. The objectives of the mission were to test sensors and spacecraft components under extended exposure to the space environment and to make scientific observations of the Moon and the near-Earth asteroid 1620 Geographos. Observations incorporated imaging at various wavelengths including UV and infrared, laser ranging altimetry, and charged particle measurements and were to assess the surface mineralogy of the Moon and Geographos; obtain lunar altimetry from 60° N to 60° S latitude; and determine the size, shape, rotational characteristics, surface properties, and cratering statistics of Geographos.

Clementine was launched on January 25, 1994, from Vandenberg Air Force Base aboard a Titan IIG rocket. It was the first U.S. spacecraft launched to the Moon in more than 20 years.[291] After launch, the spacecraft remained in a temporary orbit until February 3, when a solid-propellant rocket ignited to send the vehicle toward the Moon. After two Earth flybys, on February 5 and February 15, it achieved lunar insertion on February 19. Lunar mapping took place during approximately two months in two parts. The first part consisted of a 5-hour elliptical polar orbit with a perilune of about 400 kilometers (249 miles) at 28° S latitude.[292] After one month of mapping, the orbit was rotated to a perilune of 29° N latitude, where it remained for one more month. This allowed global imaging as well as altimetry coverage from 60° S to 60° N.

During the mission's 71 days in lunar orbit, Clementine systematically mapped the lunar surface, transmitting about 1.6 million digital images to produce the first global digital map of the Moon. The digital data set covered 38 million square kilometers (14.7 million square miles) mapped in 11 colors in the visible and near infrared parts of the spectrum. By combining information obtained through 11 filters, multispectral image data was used to map the distribution of lunar rock and soil types. The mission also provided tens of thousands of high resolution and mid-infrared thermal images. The spacecraft produced views of previously unknown regions of the Moon, as well as areas already known but gathered from a different and unique perspective. Scientists measured the topography of large, ancient impact features, including the largest and deepest impact basin known in the solar system, extending some 1,600 miles (2,570 kilometers) in diameter and more than 7 miles (11 kilometers) deep.[293]

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[291] Asif Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, pp. 155–156.

[292] Lunar orbit closest to the Moon.

[293] "Clementine Produces First Global Digital Map of Moon," *NASA News* Release 94-84, May 26, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-084.txt* (accessed September 28, 2005).

The spacecraft used a radar-based technique to detect what appeared to be ice deposits in permanently shadowed regions of the lunar south pole (see figure 4-63). The project science team concluded that its radar signal detected from 110 million to 1.1 billion tons of water ice, over an upper area limit of 5,500 square miles (14,245 square kilometers) of south pole terrain. In December 1996, NASA and the DOD announced jointly that analysis of data obtained two years earlier suggested the "existence of ice in the permanently shaded south polar region of the Moon . . . ."[294] The Lunar Prospector[295] discovered further evidence of lunar ice in 1998. Indications, however, after the controlled crash of the Lunar Prospector into a crater near the south pole of the moon in 1999 "produced no observable signature of water."[296] Further radar studies using the Arecibo Observatory in Puerto Rico in 2003 produced no suggestion of large amounts of water ice, leading scientists to conclude that, if ice existed, it was widely scattered.[297]

After successfully mapping the entire surface of the Moon and completing 297 orbits on May 3, 1994, controllers fired Clementine's thrusters to inject it on a trajectory toward an August 24 rendezvous with the asteroid 1620 Geographos. However, the satellite suffered an on-board malfunction on May 7 preventing Clementine from performing the planned close flyby of Geographos and also from pointing its cameras and sensors. Preliminary analysis traced the cause of the malfunction to the on-board computer that controlled most of the satellite's systems and attitude control thrusters. The computer activated several thrusters during a 20-minute telemetry interrupt with the ground station, which depleted all the fuel in the attitude control system tanks. The spacecraft went into an uncontrollable tumble at about 80 revolutions per minute with no spin control.

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[294] "Statement from Dr. Wesley Huntress, Associate Administrator, Office of Space Science, on Clementine Ice Discovery," *NASA News* Release,(no number), December 3, 1996, (NASA History Office Folder 5728). Also "Clementine–DSPSE," *http://www.cmf.nrl.navy.mil/clementine.html* (accessed September 2, 2005). "DOD News Briefing: Discovery of Ice on the Moon," United States Department of Defense, *http://www.dod.mil/transcripts/1996/t120496_t1203moo.html* (accessed September 27, 2005).

[295] "Lunar Prospector Finds Evidence of Lunar Ice," *HQ Bulletin* (March 23, 1998): 3 (NASA History Office Folder 5728).

[296] "No Water Ice Detected from Lunar Prospector Impact," *NASA News* Release 99-119, October 13, 1999, *http://nssdc.gsfc.nasa.gov/planetary/text/lp_pr_19991013.txt* (accessed September 27, 2005).

[297] "Arecibo Radar Shows No Evidence of Thick Ice at Lunar Poles, Despite Data from Previous Spacecraft Probes, Researchers Say," *Cornell News*, November 12, 2003, *http://www.news.cornell.edu/releases/Nov03/radar.moonpoles.deb.html* (accessed May 20, 2006). Also Rick Callahan, "Water on the Moon? Scientists Await Definitive Answer," November 12, 2003, *http://www.space.com/scienceastronomy/moon_ice_030112.html* (accessed May 20, 2006). Mike Nolan and Ellen Howell, "Don Campbell Steps Down," *NAIC/AO Newsletter*, no. 37 (April 2004), National Astronomy and Ionosphere Center, Arecibo Observatory, *http://www.naic.edu/%7Enewslet/no37/NAICNo37.pdf* (accessed May 20, 2006).

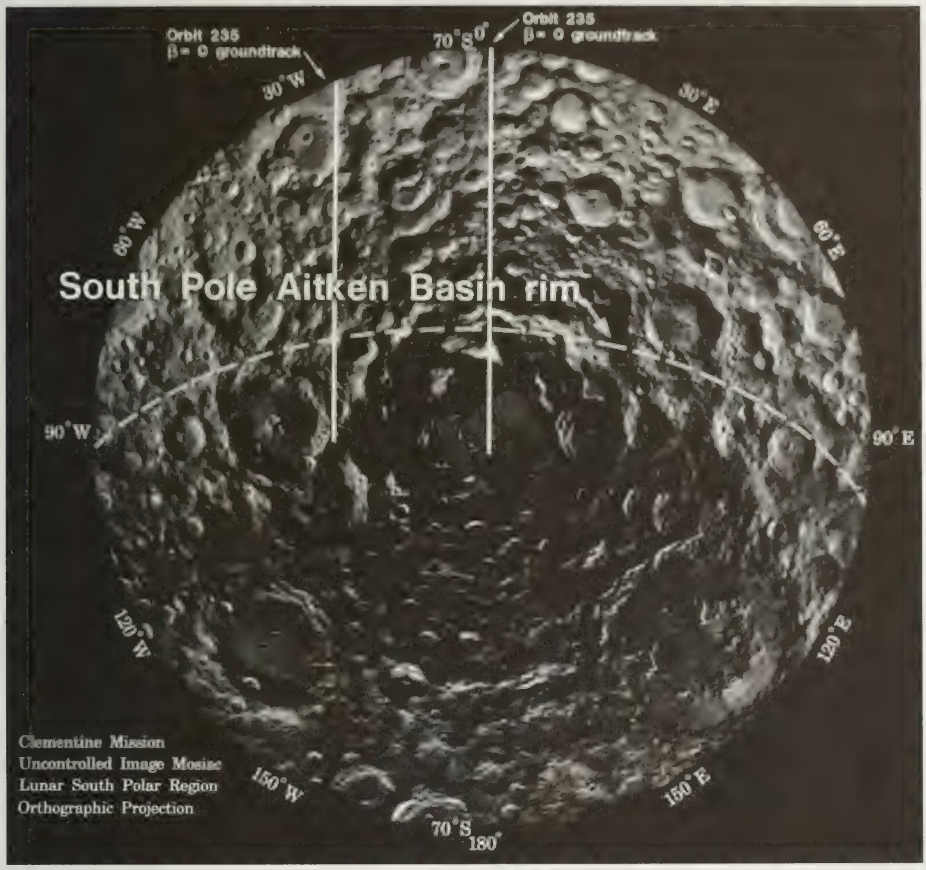
Orbit 235
β= 0 groundtrack
70°S 0°
Orbit 235
β= 0 groundtrack
30°W
30°E
60°W
60°E
South Pole Aitken Basin rim
90°W
90°E
120°W
120°E
150°W
150°E
70°S
180°
Clementine Mission
Uncontrolled Image Mosaic
Lunar South Polar Region
Orthographic Projection

Figure 4–63. South Pole of the Moon with Ice Marked in Blue. (Naval Research Lab Photo http://www.cmf.nrl.navy.mil/clementine/water/moon_ice.JPG*)*

Controllers were forced to cancel the journey to Geographos and return the vehicle to the vicinity of Earth where engineering studies continued and the spacecraft was to test sensor resistance during repeated passes through the Van Allen belts. To accomplish this, it would be necessary to prevent Clementine from returning to the vicinity of the Moon because that would put the spacecraft into orbit around the Sun. However, because of poor Sun angles, the solar panels did not generate enough power to keep the spacecraft far enough from the Moon, lunar gravity took control of Clementine, and the spacecraft slipped into orbit around the Sun. Spacecraft operations were terminated on August 8, 1994.

The spacecraft remained inoperative with a discharged battery for about six months until more optimal Sun angles provided battery charging and automatic heaters warmed the spacecraft.[298] Contact using NASA's DSN was first attempted on February 8, 1995, and the first intermittent radio signals were received from Clementine on February 20. Full engineering studies began on March 17, and positive assessments of the spacecraft's health and functionality were made. Based on those reviews, a number of engineering experiments were conducted including slowing the spin rate by firing the propulsion system. Sensor images were taken and stored on board. Since the distance from Earth was growing daily, poor signals prevented full image downlinks. However, substantial data was obtained on the performance of the spacecraft and its components in deep space under stressful conditions. The last spacecraft communications occurred on May 10, 1995. Official notice was given to the DSN to discontinue mission support on July 12, 1995.[299]

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[298] Siddiqi, p. 155.

Clementine was managed by the Ballistic Missile Defense Organization and built by the Naval Research Laboratory (NRL). Its instruments were constructed by industry and the Lawrence Livermore Laboratory. NASA researchers served on the science team, and the Agency provided lunar and asteroid navigation and use of its DSN. This landmark project demonstrated that small, highly capable satellites could be built and launched for less than $100 million and in less than two years, using advanced miniaturized technology and a streamlined management approach.[300] Table 4–72 provides mission details.

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Mars Missions

Exploration of Mars was a prime focus of NASA's planetary missions beginning with the 1965 Mariner 4 mission and continuing with the Viking lander missions of the 1970s. After Viking, 17 years passed before the next attempt—the unsuccessful 1992 Mars Observer mission. Four years later, NASA was more successful; the two missions launched by the United States succeeded.[301] The Mars Global Surveyor was first in the Mars Surveyor series of spacecraft missions to Mars to be launched at "each opportunity" (every 26 months when the position of the two planets made for optimum travel time) over the next decade. This mission carried six scientific instruments to study the Martian atmosphere, surface, and interior.

Launched a month later, the Mars Pathfinder, a mission in the Discovery Program, carried a lander and small rover robot named Sojourner. This mission, which captured the attention of people worldwide, focused on the following three major areas of investigation: the search for evidence of past life on Mars; understanding the Martian climate and its lessons for the past and future of Earth's climate; and understanding the geology and resources that could be used to support future human missions to Mars. The unifying theme of the Mars exploration program was the search for water—a key requirement for life.

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[299] Paul A. Regeon et al, "The Clementine Lunar Orbiter," *www.pxi.com/praxis_publicpages/pdfs/Lun_Orb_Gifu.pdf* (accessed September 28, 2005).

[300] "Clementine Failure," *Satellite News*, May 29, 1994, *http://www.totse.com/en/media/cable_and_satellite_television_hacks/satnews.html* (accessed September 29, 2005).

[301] The Russian Mars '96 mission to Mars was unsuccessful because of a launch failure.

Taking advantage of the late 1998/early 1999 Mars launch opportunity, NASA launched two additional Mars missions. Both the Mars Climate Orbiter and the Polar Lander failed.

Mars Observer

After a 17-year gap since the last U.S. mission to Mars, NASA launched the Mars Observer on September 25, 1992. The spacecraft was developed from a commercial, Earth-orbiting communications satellite converted into an orbiter for Mars. The payload of science instruments was to study the surface, atmosphere, interior, and magnetic field of Mars from Martian orbit. The instruments focused on Martian geology, geophysics, and climate. The spacecraft also carried a radio relay package to receive information from the planned Mars Balloon Experiment for retransmission back to Earth carried on the future Soviet Mars '94 mission. The Mars Observer mission was designed to operate for one full Martian year (687 Earth days) to permit observations of the planet through its four seasons.

At the end of 337 days traveling toward Mars, the mission ended on August 22, 1993, when contact was lost with the spacecraft shortly before it was to enter orbit around Mars. No significant scientific data was returned.

An independent investigation board convened to determine the cause of the failure. It reported that the most probable cause was a leak that had continued during the spacecraft's 11-month flight to Mars, causing tubing to rupture. The released helium and monomethyl hydrazine put the spacecraft into a spin. The high spin rate caused the spacecraft to go into "contingency mode," interrupting the stored command sequence and failing to switch on the transmitter. The released fuel most likely also damaged critical electrical circuits.[302]

The Mars Observer was to have been the first in a series of lower-cost spacecraft to Mars. But it had been many years since NASA had sent a spacecraft to Mars, and scientists were anxious to include larger numbers of more sophisticated instruments. Costs and the development schedule both grew, as the mission took 11 years to launch from the time it was conceived in 1981; the final cost was more than $800 million. The resulting spacecraft had more capabilities but did not turn out to be more reliable. Observer's failure helped push the Agency toward the "faster, better, cheaper" approach, where several smaller missions could be launched for the price of one large, expensive mission.[303] Table 4–73 provides further mission details.

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[302] "Mars Observer Investigation Report Released," *NASA News* Release 94-1, January 5, 1994, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1994/94-001.txt* (accessed August 18, 2005).

[303] McCurdy, *Faster, Better, Cheaper*, pp. 18–19, 120.

Mars Global Surveyor

In 1993, NASA began the Mars Surveyor Program with the objective of conducting a series of missions to explore Mars. NASA established and gave responsibility to the Mars Program Office for defining objectives for sending two missions to Mars at each biennial launch opportunity. JPL established a project office to manage development of specific spacecraft and mission operations.

The first of these missions was the Mars Global Surveyor, the first successful mission to Mars in two decades. It launched on November 7, 1996, and entered Martian orbit on September 12, 1997. After a year and a half trimming its orbit from a looping ellipse to a circular track around the planet, the spacecraft began its prime mapping mission in March 1999. It observed the planet from a low-altitude, nearly polar orbit over the course of one complete Martian year, the equivalent of almost two Earth years. Mars Global Surveyor completed its primary mission on January 31, 2001, and entered an extended mission phase.

The core of the Mars Global Surveyor spacecraft was a rectangular bus housing computers, the radio system, solid-state data recorders, fuel tanks, and other equipment. Attached to the outside were several rocket thrusters, which were fired to adjust the spacecraft's path during the cruise to Mars and to modify the spacecraft's orbit around the planet. To minimize costs, most of the spacecraft's instruments and electronics were duplicates or spares from the Mars Observer mission. The spacecraft design also incorporated new hardware—the radio transmitters, solid state recorders, propulsion system, and composite material bus structure.

The spacecraft orbited the planet to allow one side of the bus, called the nadir deck, to always face the Martian surface. The science instruments–the MOC, MOLA, ER, and the TES—were attached to the nadir deck, along with the Mars Relay Radio System. The magnetometer sensors were mounted on the ends of the solar arrays.

The bus had two solar array wings that always pointed toward the Sun. They provided 980 watts of electricity for operating the spacecraft's electronic equipment and for charging the nickel hydrogen batteries. The batteries provided electricity when the spacecraft was mapping the dark side of Mars. The dish-shaped high-gain antenna was mounted on the end of a boom, preventing the solar arrays from blocking the spacecraft's view of Earth while it orbited Mars. This steerable antenna pointed toward Earth even though the spacecraft's position was continuously adjusted during mapping to keep the nadir deck pointed toward Mars. The radio system, which included the high-gain antenna, also functioned as a science instrument. Researchers used it in conjunction with NASA's DSN ground stations for the radio science investigations. Figure 4–64 shows a diagram of the spacecraft. To maintain appropriate operating temperatures, most of the outer exposed parts of the spacecraft and the science instruments were wrapped in thermal blankets.

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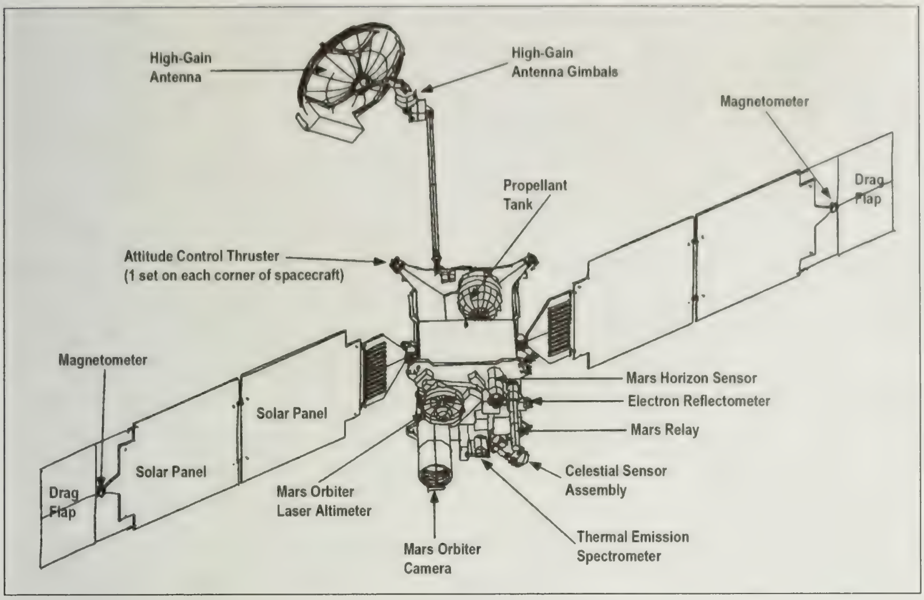
High-Gain Antenna
High-Gain Antenna Gimbals
Magnetometer
Propellant Tank
Drag Flap
Attitude Control Thruster (1 set on each corner of spacecraft)
Magnetometer
Solar Panel
Solar Panel
Drag Flap
Mars Horizon Sensor
Electron Reflectometer
Mars Relay
Celestial Sensor Assembly
Mars Orbiter Laser Altimeter
Thermal Emission Spectrometer
Mars Orbiter Camera

Figure 4–64. Mars Global Surveyor.[304]

The spacecraft used aerobraking to trim its initial, highly elliptical capture orbit and lower it to a nearly circular mapping orbit. Aerobraking had been successfully demonstrated during the 1988 Magellan mission to Venus. Aerobraking was necessary because the mass limits imposed by the lifting capabilities of the Delta II launch vehicle prevented the spacecraft from carrying enough propellant to put itself into its final low-altitude mapping orbit with an engine firing. With aerobraking, the spacecraft dipped into the upper fringes of the Martian atmosphere during each of its orbits every time it reached the point in its orbit closest to the planet. Friction generated by movement of drag panels at the ends of the solar panels slowed the spacecraft slightly, causing the spacecraft to lose some of its momentum during each orbit. This lowered the spacecraft's orbit point that was farthest from Mars.

Following its capture into Mars orbit on September 12, 1997, the Mars Global Surveyor made its closest approach to Mars, beginning an aerobraking phase intended to last for four months but which took a year and a half to complete. On September 17, 1997, the spacecraft dipped into the upper fringes of the Martian atmosphere for 27 seconds, allowing the drag on its solar panels to begin the long aerobraking process of circularizing its orbit.[305] A problem occurred on October 6 when the latch on one of the solar panels appeared to crack, and the panel flexed past its design position, moving more than 20 degrees. The Martian atmosphere had become twice as dense as it had during previous passes, thus exerting 50 percent more pressure than expected on the solar array.

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[304] "Mars Global Surveyor," Fact Sheet, Jet Propulsion Laboratory, *http://www.jpl.nasa.gov/news/fact_sheets/mgs.pdf* (accessed August 10, 2005).

[305] "Mars Global Surveyor Detects Martian Magnetic Field as Aerobraking Begins," *NASA News* Release 97-204, September 17, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-204.txt* (accessed August 11, 2005).

Mission operators raised the spacecraft's orbit on October 12 to adjust the pressure level. On November 7, the mission operators resumed lowering the spacecraft's orbit around Mars at a more gradual pace. As a result, aerobraking took much longer than anticipated, extending the phase by several months and changing the spacecraft's final science mapping orbit.[306] Originally, the mapping phase was to have begun in the spring of 1998; but because of the delay, the mapping phase did not begin until more than a year later.[307] In the meantime, on March 26, 1998, aerobraking was suspended until the spacecraft moved into the proper position with respect to the Sun before beginning the next round on September 23, 1998. To maximize the efficiency of the mission, beginning on March 27, 1998, the spacecraft turned on its payload of science instruments and began a set of scientific observations from its interim elliptical orbit.

When aerobraking ended and the spacecraft was set in its mapping orbit with systems deployed and instruments checked out, the Mars Global Surveyor started creating a global portrait of Mars by traveling over a different part of Mars each orbit. The primary mapping mission began on April 4, 1999.[308] It lasted nearly one complete Martian year, the equivalent of nearly two Earth years, ending on January 31, 2001, when the mapping mission moved immediately into the extended mission phase.

The mission studied the entire Martian surface, atmosphere, and interior. It sent thousands of images back to Earth and returned more data about the planet than all other Mars missions combined. Early in the mission, scientists used information from the spacecraft's magnetometer to confirm the existence of a planet-wide magnetic field. Its laser altimeter provided the first three-dimensional views of the Martian north pole and insight into the processes shaping it. It imaged the Viking 1 and 2 landing sites, the Mars Pathfinder landing site, and the "Face on Mars" during passes over the planet (see Figure 4–65). For the first time in Mars exploration, a spacecraft captured the full evolution of a Martian dust storm.

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[306] "Mars Global Surveyor To Resume Aerobraking," *NASA News* Release 97-249, October 30, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-249.txt* (accessed August 11, 2005).

[307] MarsNews.com, *http://www.marsnews.com/missions/mgs/* (accessed August 10, 2005).

[308] "MSOP Status Report Overview, Prepared by Mars Surveyor Operations Project Manager," NASA Jet Propulsion Laboratory, April 9, 1999, *http://marsprogram.jpl.nasa.gov/mgs/status/wkreport/current.html* (accessed August 11, 2005).

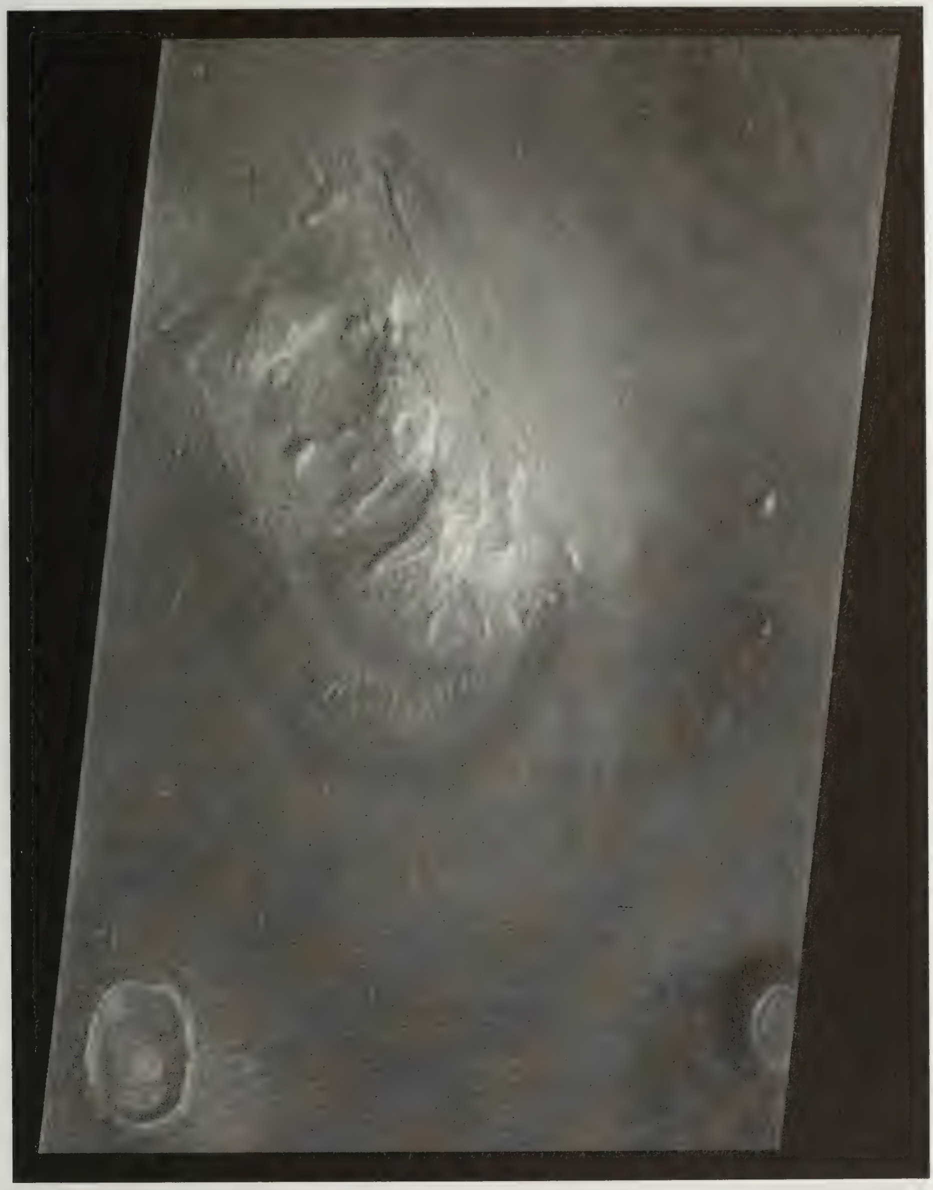

Figure 4–65. On April 6, 1998, approximately 375 seconds after the Mars Global Surveyor spacecraft made its 220th close approach to Mars, it acquired an image of a "face" from a distance of 444 kilometers (275 miles). The image had a resolution of 4.3 meters (14.1 feet) per pixel, making it 10 times better than the image acquired by the Viking spacecraft in 1976. The full image covered an area 2.7 miles (4.4 km) wide and 25.7 miles (41.5 km) long. Image processing was applied to improve the visibility of features. What some saw to be eyes, a nose, and lips were most likely peaks and ridges. This photo shows part of the image, containing the "face" and a couple of nearby impact craters and hills. It was "cut" out of the full image and reproduced separately. (NASA-JPL Photo No. PIA01440)

The spacecraft also returned new information about the deeply layered terrain and mineral composition of the Martian surface and highly magnetized crustal features, providing clues about the planet's interior (see Figure 4–66). Close-up views of the Elysium Basin revealed the first evidence of huge plates of solidified lava. The views also provided evidence for active dunes near the planet's north pole; the dunes had sands that hopped or rolled across the surface after the surveyor approached Mars. New temperature data and close-up images of the Martian moon Phobos indicated that millions of years of meteoroid impacts had pounded the surface of that small body into powder at least 1 meter (3 feet) thick; some impacts started landslides that left dark trails marking the steep slopes of giant craters. Data from the thermal emission spectrometer revealed new mineralogical and topographic evidence suggesting that Mars once had abundant water and thermal activity. Table 4–74 provides additional mission details.

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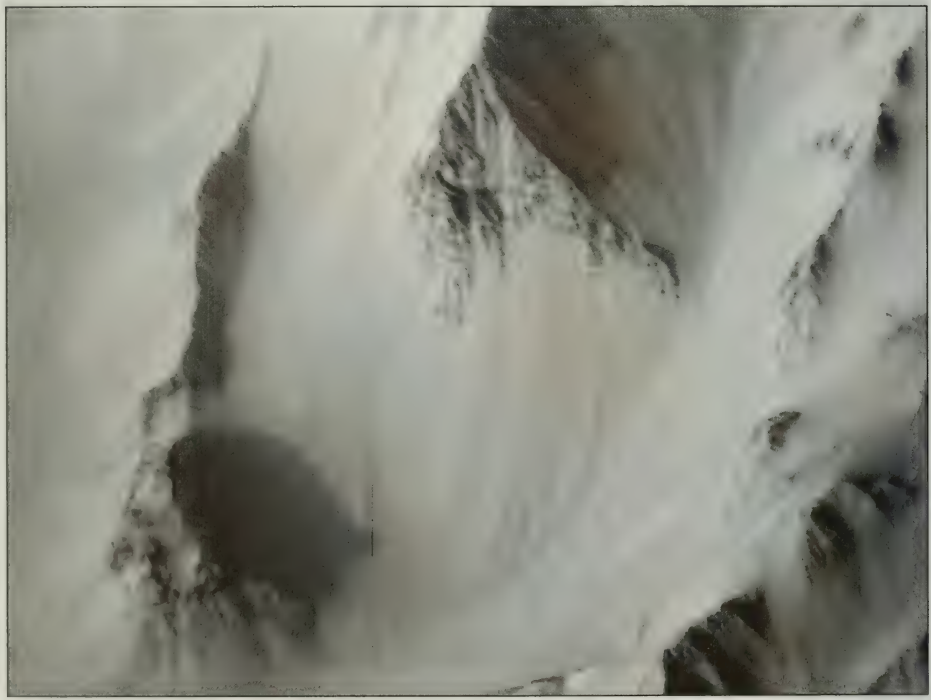

Figure 4–66. This image revealed light and dark layers in the rock outcrops of the canyon walls. In the notable triangular mountain face (at center), some 80 layers, typically alternating in brightness and varying in thickness from 5 meters to 50 meters (16 feet to 160 feet), are clearly visible. This type of bedrock layering had never been seen before in Valles Marineris. It called into question common views about the upper crust of Mars, for example, that there was a deep layer of rubble underlying most of the Martian surface, and argued for a much more complex early history of the planet. (MOC Image No. 560380579.1303 P013-03. NASA/JPL/ Malin Space Science Systems)

Mars Pathfinder

The Mars Pathfinder, a Discovery mission, was the last of the three 1996 Mars missions to leave Earth, but it was the first to arrive because of its shorter flight path. The mission demonstrated an innovative approach to landing an instrumented lander and free-ranging robotic rover on the surface of Mars. It also returned an unprecedented amount of data. The lander, formally named the Carl Sagan Memorial Station following its successful touchdown, and the microrover, named Sojourner after U.S. civil rights crusader Sojourner Truth, both outlived their design lives—the lander by nearly 3 times, and the rover by 12 times.

The spacecraft used an original method to directly enter the Martian atmosphere, assisted by a parachute to slow its descent and a giant system of airbags to cushion the impact (see Figure 4–67).

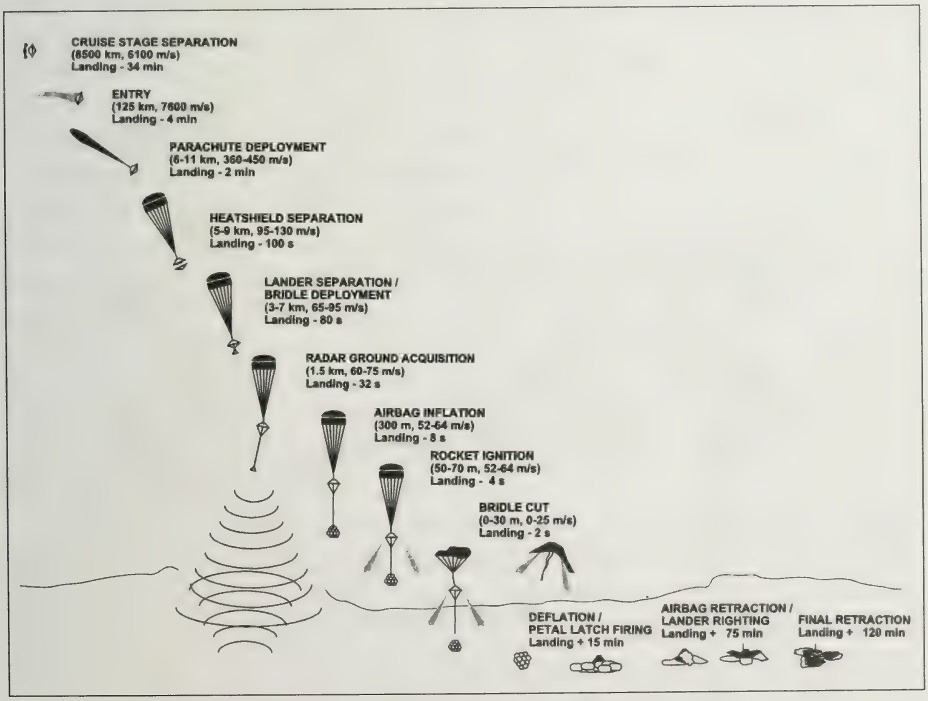
CRUISE STAGE SEPARATION
(8500 km, 6100 m/s)
Landing - 34 min
ENTRY
(125 km, 7600 m/s)
Landing - 4 min
PARACHUTE DEPLOYMENT
(6-11 km, 360-450 m/s)
Landing - 2 min
HEATSHIELD SEPARATION
(5-9 km, 95-130 m/s)
Landing - 100 s
LANDER SEPARATION / BRIDLE DEPLOYMENT
(3-7 km, 65-95 m/s)
Landing - 80 s
RADAR GROUND ACQUISITION
(1.5 km, 60-75 m/s)
Landing - 32 s
AIRBAG INFLATION
(300 m, 52-64 m/s)
Landing - 8 s
ROCKET IGNITION
(50-70 m, 52-64 m/s)
Landing - 4 s
BRIDLE CUT
(0-30 m, 0-25 m/s)
Landing - 2 s
DEFLATION / PETAL LATCH FIRING
Landing + 15 min
AIRBAG RETRACTION / LANDER RIGHTING
Landing + 75 min
FINAL RETRACTION
Landing + 120 min

Figure 4–67. Mars Pathfinder Entry, Descent, and Landing.

The Mars Pathfinder touched down on July 4, 1997, at 16:57 Universal Time at a velocity of about 18 meters per second (40 miles per hour). It bounced about 15 meters (50 feet) into the air, bouncing another 15 times and rolling before coming to rest approximately 2.5 minutes after impact and about 1 kilometer (1.2 miles) from the initial impact site. One of the rockiest parts of Mars, the landing site in the Ares Vallis region was at 19.33°N, 33.55°W in Mars' Northern Hemisphere. This site was chosen because scientists believed it was a relatively safe surface to land on and it contained a wide variety of rocks deposited during an ancient flood.

The Mars Pathfinder's Sojourner Rover (formally named the Microrover Flight Experiment) rolled onto the Martian surface on July 6 at about 05:40 Universal Time. The rover was a technology experiment itself, designed to determine microrover performance in the poorly understood Martian terrain so that future rover designs would be effective in navigating and moving about the surface of Mars. The rover was limited to a weight of 11.5 kilograms (25.4 pounds). Another 6 kilograms (13.3 pounds) were allocated to lander-mounted rover telecommunications equipment, structural support of the rover, and its deployment mechanisms. The microrover had a height of 28 centimeters (10.9 inches), with ground clearance of 13 centimeters (5 inches) (see figure 4–68).

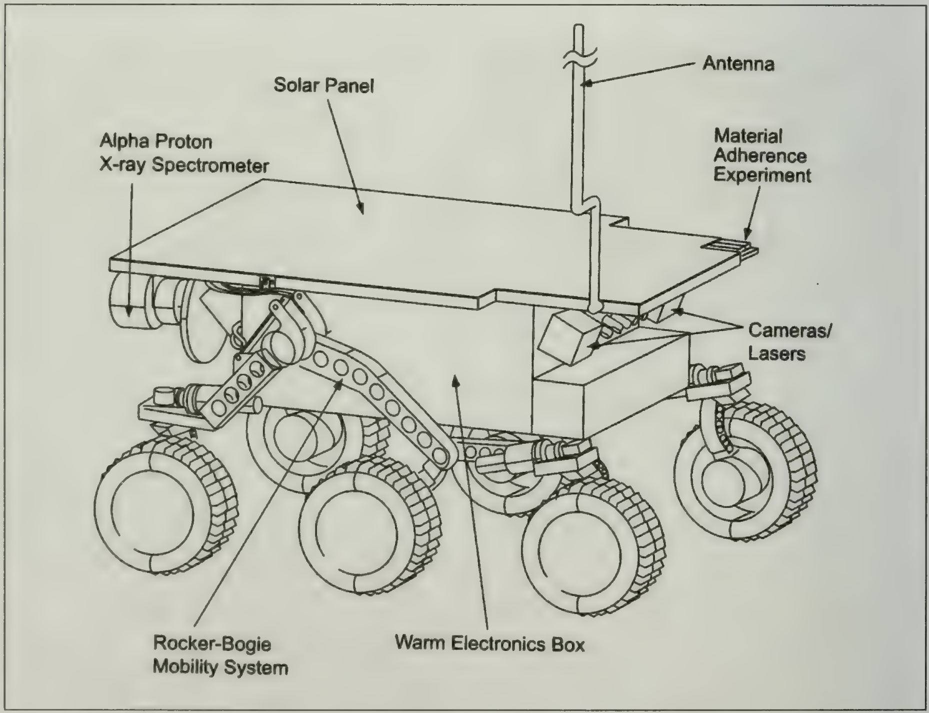

Figure 4–68. Mars Pathfinder's Sojourner Microrover.

The allowed lander stowage space for the Sojourner microrover was only 20 centimeters (7.8 inches), forcing it to "squat" to a height of 18 centimeters (7 inches) with its chassis and wheels folded up during its trip to Mars. Once its solar cells were exposed to the Sun, the Sojourner powered up and unfolded to its full height before leaving the lander.

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The microrover was a six-wheeled vehicle of a rocker-bogie design, allowing it to travel over obstacles a wheel diameter (13 centimeters or 5.1 inches) in size. Each wheel was independently actuated and geared, providing superior climbing capability in soft sand. The front and rear wheels could be steered independently, allowing the vehicle to turn in place. The vehicle had a top speed of 0.4 meters (1.3 feet) per minute. A 22-square-meter (237-square-foot) solar panel powered the microrover. Nine batteries backed up the solar panel. The combined panel/battery system allowed microrover power users to draw up to 30 watts of peak power.[309] Microrover components not designed to survive ambient Mars temperatures, which reach -110°C (-166°F) during a Martian night, were contained in the warm electronics box, an insulated and heated container maintaining components between -40°C (-40°F) and +40°C (104°F) during a Martian day.

An integrated set of computing and power distribution electronics provided control. The on/off switching of the drive or steering motors controlled vehicle motion. While stopped, the computer updated its measurement of distance traveled and heading using the averaged odometry and on-board gyroscope. This provided an estimate of progress to the goal location.

Modems on the microrover and lander provided command and telemetry. The microrover was the link commander of the ultra high frequency system. During the day, the microrover regularly requested transmission of any commands sent from Earth and stored on the lander. When commands were unavailable, the microrover transmitted any telemetry collected during the last interval between communication sessions. The telemetry received by the lander from the microrover was stored and forwarded to Earth. In addition, this communication system provided a "heartbeat" signal during vehicle driving. While stopped, the microrover sent a signal to the lander. Once acknowledged by the lander, the microrover proceeded to the next stopping point along its route.

At the end of each sol of microrover travel, the camera system on the lander took a stereo image of the vehicle in the terrain. Those images were displayed at the control station. The operator could designate points in the terrain to serve as goal locations for the microrover. The coordinates of these points were transferred into a file containing the commands for execution by the microrover on the next sol. In addition, the operator used a model that, when overlayed on the image of the vehicle, measured the location and heading of the vehicle. This information was also transferred into the command file to be sent to the microrover on the next sol to correct any navigation errors.[310]

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[309] "A Description of the Rover Sojourner," *http://mpfwww.jpl.nasa.gov/MPF/rover/descrip.html* (accessed August 23, 2005).

[310] "A Description of the Rover Sojourner," *http://mpfwww.jpl.nasa.gov/MPF/rover/descrip.html* (accessed August 23, 2005).

The Pathfinder lander represented very advanced technology. The lander's three solar panels supplied up to 1,200 watt-hours of electrical power per day. At night, the lander operated on rechargeable silver-zinc batteries with a capacity of more than 40 amp-hours. For communications, Pathfinder had a high-gain antenna for high-speed, 2,250-bit-per-second communications with NASA's DSN. Its low-gain antenna sent information at a lower rate of 40 bits per second but did not need to be actively pointed at Earth.

The Imager for Mars Pathfinder was the Pathfinder's main imaging system. The Atmospheric Structure Instrument/Meteorology Package (ASI/MET) mast, the Pathfinder's weather tower, collected atmospheric information from a variety of temperature, pressure, and wind sensors. See Figure 4–69 for a drawing of the lander and Table 4–75 for further mission details.[311]

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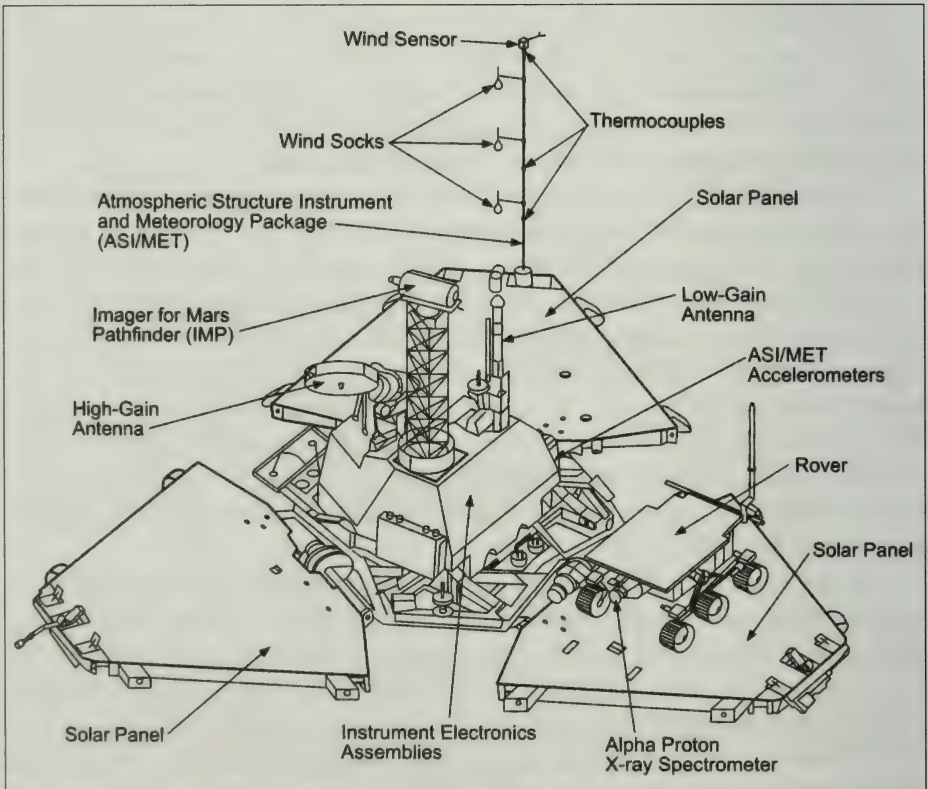
Wind Sensor
Thermocouples
Wind Socks
Atmospheric Structure Instrument and Meteorology Package (ASI/MET)
Solar Panel
Low-Gain Antenna
Imager for Mars Pathfinder (IMP)
ASI/MET Accelerometers
High-Gain Antenna
Rover
Solar Panel
Solar Panel
Instrument Electronics Assemblies
Alpha Proton X-ray Spectrometer

Figure 4–69. Mars Pathfinder Lander.

From landing until the final data transmission on September 27, 1997, the Mars Pathfinder returned 2.3 billion bits of information, including more than 16,500 images from the lander and 550 images from the rover, as well as more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors. Findings from the investigations carried out by scientific instruments on both the lander and rover suggested that Mars was once warm and wet, with water existing in its liquid state and a thicker atmosphere.[312]

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[311] "Pathfinder and Sojourner Explore Mars," *http://www.spacetoday.org/SolSys/Mars/MarsExploration/MarsPathfinder.html* (accessed August 23, 2005).

Mars '96

Mars '96 (originally called Mars '94) was a Russian mission consisting of an orbiter, two soft landers, and two surface penetrators to study Mars. The orbiter carried 12 instruments, as well as seven plasma-measuring instruments and three astrophysics instruments. Additional instruments were located on the landers and penetrators for measurements at the Martian surface (see Table 4–76). The United States contributed an instrument called the Mars Oxidant Experiment, an experiment that was to fly on one of the Russian landers or "small autonomous stations."

The main scientific objective of this mission was to investigate the evolution of the Martian atmosphere, surface, and interior. The mission was to consist of seven phases: launch and injection toward Mars; cruise (including two midcourse corrections); small station release and orbiter deflection maneuver; orbit insertion; orbit corrections; penetrator release; and mapping operations.

The mission lifted off on November 16, 1996, from Baikonur Cosmodrome in the Republic of Kazakhstan on a Proton launch vehicle. The spacecraft was not inserted into the interplanetary trajectory to Mars because of a malfunction in Block D (the third stage of the rocket). During the third revolution around Earth, the spacecraft reentered Earth's atmosphere and fell into the Pacific Ocean.[313] The spacecraft sank carrying 270 grams (9.5 ounces) of plutonium-238, part of its energy source.

Mars 1998–1999 Missions

In 1995, the Mars Program Office identified two missions for launch during late 1998–early 1999, the Mars Climate Observer and the Mars Polar Lander. To manage the missions, JPL created the Mars Surveyor Project '98 Office, an office responsible for designing the missions, developing both spacecraft and all payload elements, and integrating, testing, and launching both flight systems. In March 1996, after formation of the project office, the Mars Surveyor Program established the Mars Surveyor Operations Project, which was tasked with operating all Mars Surveyor Program missions.[314]

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[312] "Mars Pathfinder," NASA's Mars Exploration Program, NASA Jet Propulsion Laboratory, *http://mars.jpl.nasa.gov/missions/past/pathfinder.html* (accessed August 11, 2005).

[313] "Robotic Spacecraft Mission to Mars: Summary," *http://www.iki.rssi.ru/mars96/mars96hp.html* (accessed September 20, 2005).

[314] Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," March 13, 2000, p. 10 (NASA History Office Folder 17919).

Taking advantage of the December 1998–January 1999 launch opportunity, NASA launched two missions to Mars. Both missions were designed, and their payloads selected, to address the science theme "Volatiles and Climate History" on Mars. They were to focus directly on the climate-history and resources themes of the Mars Surveyor Program while supporting the life-on-Mars theme through characterization of climate change and its evolving impact on the distribution of water.

The Mars Climate Orbiter and Mars Polar Lander Missions' scientific strategy was the following:

- Use seasonal and diurnal cycles of dust, water, and carbon dioxide to understand the processes of climate change during longer time scales.
- Characterize global atmospheric structure and circulation to explain the roles of atmospheric transport of volatiles and dust.
- Land on, and explore, a site having physical evidence of ancient climates, atmospheric evolution, and more recent, possibly periodic climate change.
- Locate surface ice reservoirs and search for local subsurface ice.
- Acquire data needed to validate and extend model simulations of climate processes and climate change.
- Emphasize comparative study of the climates of Earth and Mars and their potential implications for the origin and development of life.
- The major scientific measurement objectives for the Mars Surveyor Program 1998 missions were the following:
- Systematically observe the thermal structure and dynamics of the global atmosphere and the radiative balance of the polar regions, thereby providing a quantitative climatology of weather regimes and daily to seasonal processes.
- Determine the variations with time and space of the atmospheric abundance of dust and of volatile material (i.e., carbon dioxide and water, both vapor and ice) for one full Martian year.
- Identify surface reservoirs of volatile material and dust and observe their seasonal variations; characterize surface compositional boundaries and their changes with time; and search for near-surface ground ice in the polar regions.
- Explore and quantify the climate processes of dust storm onset and decay; atmospheric transport of volatiles and dust; and mass exchange between the atmosphere, surface and subsurface.
- Search for evidence characterizing ancient climates and more recent periodic climate change.

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Mars Climate Orbiter

The Mars Climate Orbiter was designed to function as an interplanetary weather satellite and communications relay for the Mars Polar Lander. The orbiter, a combined graphite composite-aluminum honeycomb structure similar to the material used on commercial aircraft, carried two science instruments: a copy of an atmospheric sounder that flew on the Mars Observer spacecraft lost in 1993, and a new, lightweight color imager combining wide-angle and medium-angle cameras (see Figure 4–70).[315] During orbiter development, NASA officials applied the guiding principles of the "faster, cheaper, better" Discovery Program, capping mission costs and requiring the spacecraft to fit on a Delta II launch vehicle.[316]

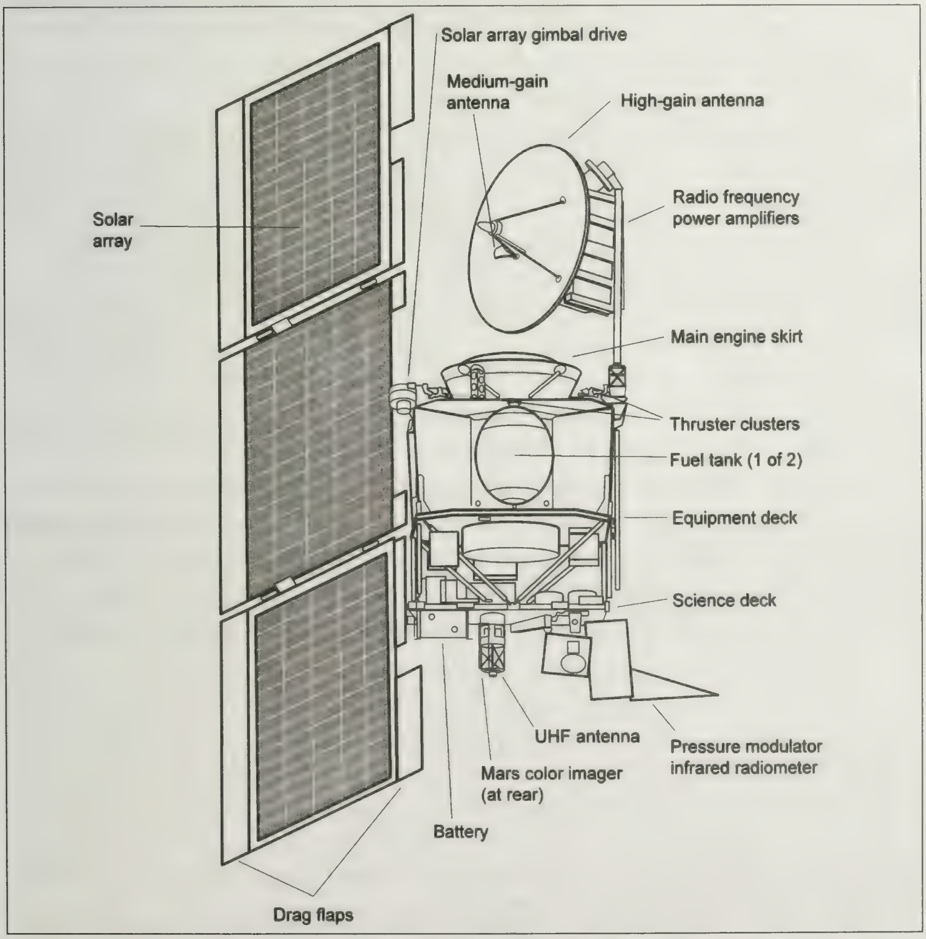
Solar array gimbal drive
Medium-gain antenna
High-gain antenna
Radio frequency power amplifiers
Solar array
Main engine skirt
Thruster clusters
Fuel tank (1 of 2)
Equipment deck
Science deck
UHF antenna
Pressure modulator infrared radiometer
Mars color imager (at rear)
Battery
Drag flaps

Figure 4–70. Mars Climate Orbiter.[317]

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[315] "Mars Climate Orbiter," NASA's Mars Exploration Program, *http://mars.jpl.nasa.gov/missions/past/climorb.html* (accessed August 11, 2005).

[316] McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program,* p. 56.

[317] "Mars Climate Orbiter Arrival Press Kit," September 1999, p. 21, *http://www.jpl.nasa.gov/news/press_kits/mcoarrivehq.pdf* (accessed August 11, 2005).

The spacecraft was launched on December 11, 1998, on top of a Delta II ELV from Cape Canaveral Air Force Station, Florida. Nine and one-half months after launch, in September 1999, the spacecraft was to fire its main engine to achieve an elliptical orbit around Mars. It then was to skim through the Martian upper atmosphere for several weeks, using aerobraking to move into a lower circular orbit. Friction against the spacecraft's single 5.5-meter (18-foot) solar array was to lower the altitude of the spacecraft as it dipped into the atmosphere, reducing its orbital period from more than 14 hours to 2 hours.[318]

Until the morning of September 23, 1999, all information coming from the orbiter looked normal. At approximately 2 a.m. Pacific Daylight Time, the orbiter fired its main engine to go into orbit around Mars. The engine burn began as planned 5 minutes before the spacecraft passed behind the planet as seen from Earth. However, flight controllers did not detect a signal when the spacecraft was expected to emerge from behind the planet, and no further communication from the spacecraft was received. Later in the day, controllers announced that the spacecraft was believed lost.[319]

Almost immediately, Associate Administrator for the Office of Space Science Edward Weiler established the Mars Climate Orbiter Mission Failure Mishap Investigation Board to look independently into all aspects of the failed mission.[320] After review, the failure board determined that the spacecraft had entered the Martian atmosphere at a lower-than-expected trajectory, at approximately 60 kilometers (37 miles) rather than 150 kilometers (93 miles). The minimum survivable altitude was 85 kilometers (53 miles). According to Arthur G. Stephenson, head of the Failure Board, the "root cause" of the loss of the spacecraft was "the failed translation of English units into metric units in a segment of ground-based, navigation-related software."[321] This "failure to recognize and correct an error in the transfer of information between the Mars Climate Orbiter spacecraft team in Colorado and the mission navigation team in California," information critical to the maneuvers required to place the spacecraft in proper orbit around Mars, led to spacecraft loss because of the resulting incorrect altitude.[322] Table 4–77 provides further mission details.

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[318] Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," Appendix B, p. 37 (NASA History Office Folder 17919).

[319] "NASA's Mars Climate Orbiter Believed To Be Lost," Mars Polar Lander Release, September 23, 1999, *http://mars.jpl.nasa.gov/msp98/news/mco990923.html* (accessed August 11, 2005).

[320] Mars Climate Orbiter Mishap Investigation Board, "Report on Project Management in NASA," p. 10.

[321] "Mars Climate Orbiter Failure Board Releases Report, Numerous NASA Actions Underway in Response," *NASA News* Release 99-134, November 10, 1999, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1999/99-134.txt* (accessed August 11, 2005).

[322] "Likely Cause of Orbiter Loss Identified," Jet Propulsion Laboratory, *Universe* (October 1, 1999): 1 (NASA History Office Folder 17919).

Mars Polar Lander

The Mars Polar Lander was the second of two spacecraft launched toward Mars during the December 1998–January 1999 Mars launch opportunity. Also modeled after Discovery Program projects, the Mars Polar Lander was an ambitious mission to set a spacecraft down on the frigid terrain near the edge of Mars's south polar cap and dig for water ice with a robotic arm. In addition to its instruments and experiments. The lander carried two small probes from the New Millennium Program. Called Deep Space 2, the probes were designed to smash into the Martian surface to test new technologies for future planetary descent probes. The Mars Polar Lander and Deep Space 2 were lost at arrival on December 3, 1999. See Table 4–78 for mission details.

Comet Rendezvous Asteroid Flyby–Cassini-Huygens

The CRAF and Cassini-Huygens planetary missions were to build on the discoveries made through the Pioneer and Voyager missions. They were planned initially to be built around the new Mariner Mark II spacecraft with common design, fabrication, test, and integration elements to minimize costs. Both missions had international collaborators. Germany was to provide the propulsion system and one science instrument for the CRAF mission. The ESA contributed the Huygens science probe as well as science instruments and scientist participation to Cassini. The Italian Space Agency, Agenzia Spaziale Italiana, contributed Cassini's radio antenna.

Comet Rendezvous Asteroid Flyby

The CRAF mission was proposed in October 1985 when NASA's Solar System Exploration Committee recommended authorizing a comet rendezvous/asteroid flyby in FY 1987 for a 1990–1992 launch.[323] In October 1986, NASA selected the scientific payload, and in November announced the selection of 38 possible science investigations for the CRAF mission, which would be managed by JPL. The mission would be the first to use the new Mariner Mark II spacecraft. The CRAF mission was to conduct the first long-term study of a comet and its ejected gases and assess organic molecules present at the beginning of the solar system and their potential contribution to the origin of life. The spacecraft would rendezvous with the comet Kopff in 1996, fly in formation with it for three years, and fire an instrumented penetrator into the comet's nucleus in 1997. The spacecraft also was to make close flybys of two asteroids on its way to the comet encounter.[324]

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[323] *Astronautics and Aeronautics, 1985: A Chronology* (National Aeronautics and Space Administration Special Publication-2000-4025: Washington, DC, 1988), p. 51.

[324] "NASA Selects Science Investigations for CRAF," Jet Propulsion Laboratory News Release, November 9, 1986, *http://www.jpl.nasa.gov/releases/80s/release_1986_1109.html* (accessed September 20, 2005).

Congress first funded the CRAF and Cassini missions jointly in the FY 1990 budget (prepared in 1989), contingent on a cost containment plan for the missions. Failure to stay within a set percentage of the plan's funding profile would result in termination of the CRAF mission.[325] Planned launch had by this time moved to August 1995. However, due to cost overruns and federal budget constraints, the CRAF program was cancelled in January 1992. FY 1992 funds were used to terminate the program, and any remaining funds were transferred to the Cassini program. Development of the Mariner Mark II spacecraft also was cancelled, requiring Cassini to redesign its spacecraft.

Cassini-Huygens

The Cassini-Huygens mission was a follow-on to the brief reconnaissance of Saturn performed by Pioneer 11 in 1979 and the Voyager 1 and Voyager 2 encounters in 1980 and 1981. The mission was named for two 17th century astronomers. Italian-French astronomer Jean-Dominique Cassini made several key discoveries about Saturn between 1671 and 1684 and established that Saturn's rings are split largely into two parts by a narrow gap. The Dutch scientist Christiaan Huygens discovered Titan, the largest of Saturn's moons, in 1655 and was responsible for many important Saturn findings.[326]

The mission began in 1982 when the Space Science Committee of the European Science Foundation and the Space Science Board of the National Academy of Sciences in the United States formed a joint working group. The group charter was to study possible modes of cooperation between the United States and Europe in the field of planetary science. As a result of their involvement in the studies, European scientists proposed a Saturn orbiter and Titan probe mission to the ESA, suggesting a collaboration with NASA.

In 1983, the U.S. Solar System Exploration Committee recommended that NASA include a Titan probe and radar mapper in its core program and also consider a Saturn orbiter. During 1984–1985, NASA and the ESA completed a joint assessment of a Saturn orbiter-Titan probe mission. In 1986, the ESA's Science Program Committee approved Cassini for initial conceptual study, with a conditional start in 1987.

During 1987–1988, NASA performed further design and development work on the standardized Mariner Mark II spacecraft and on a group of outer planet missions to be accomplished with the new spacecraft line. This was an early effort to reduce the cost of planetary exploration by producing multiple spacecraft for different missions made with the same basic spacecraft components off the same assembly line. The Cassini and CRAF missions were the first two missions chosen for further study. At the same time in

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[325] "Chronological History Fiscal Year 1990 Budget Submission," p. 86 (NASA History Office Folder no. 10599).

[326] "Cassini Launch Press Kit," October 1997, pp. 3–4, *http://www.jpl.nasa.gov/news/press_kits/cassini.pdf* (accessed September 20, 2005).

Europe, the ESA carried out a Titan probe conceptual study in collaboration with a European industrial consortium led by Marconi Space Systems. The ESA renamed the Titan probe Huygens as the first medium-sized mission of its Horizon 2000 space science program.

Congress approved funding for Cassini and the comet-asteroid mission in 1989, and NASA and the ESA simultaneously released announcements of opportunity for scientists to propose scientific investigations for the missions. In 1992, Congress placed a funding cap on the Mariner Mark II program that effectively ended the new spacecraft line and also cancelled the CRAF mission. Cassini was restructured to reduce total program cost, mass, and power requirements.

The design of Cassini resulted from extensive tradeoff studies that considered cost, mass, reliability, durability, suitability, and availability of hardware. Moving parts were eliminated from the spacecraft wherever the functions could be performed satisfactorily without them. Thus, early designs that had included moving science instrument platforms or turntables were discarded in favor of instruments fixed to the spacecraft body whose pointing required rotation of the entire spacecraft. Tape recorders were replaced with solid-state recorders. Mechanical gyroscopes were replaced with hemispherical resonator gyroscopes. An articulated probe relay antenna was discarded in favor of using a high-gain antenna to capture the radio signal of the Huygens probe. A deployable high-gain antenna of the type used for the Galileo mission was considered and abandoned.[327]

One Cassini component generated controversy. Cassini uses RTGs, which contain plutonium, to generate the spacecraft's electrical power. RTGs enable spacecraft to operate at significant distances from the Sun or in other areas where solar power systems are unfeasible. The United States has used RTGs on 23 missions before Cassini, including Galileo, Ulysses, the earlier Pioneer, Viking, and Voyager missions, and the Apollo Moon landers. However, despite the successful record, critics feared that an accident during the planned flyby of Earth could bring the spacecraft too close to Earth and "shoot lethal plutonium onto Earth." Critics also contended that a launch accident would result in a "radioactive shower."[328] NASA maintained that even on the three occasions when there had been malfunctions on a mission using RTGs, the generators remained intact and did not release plutonium into the environment even in an explosion. The plutonium on Cassini was well shielded from intense heat, pressure, and shrapnel. Produced by the Department of Energy exclusively for space applications, the material was processed into 72 insoluble ceramic pellets encased in iridium and high-strength graphite blocks designed to withstand reentry into Earth's atmosphere or an explosion at launch. Further, the ceramic pellets were designed to resist vaporization and would break into chunks, not powder that could be inhaled, on impact. Figure 4–71 shows a drawing of an RTG.

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[327] "Cassini-Huygens Saturn Arrival Press Kit," June 2004, pp. 11–12, *http://www.nasa.gov/pdf/60116main_cassini-arrival.pdf* (accessed September 20, 2005).

[328] "Cassini: Controversies Abound," CNN Interactive, *http://www.cnn.cm/SPECIALS/cassini/controversy* (accessed September 20, 2005).

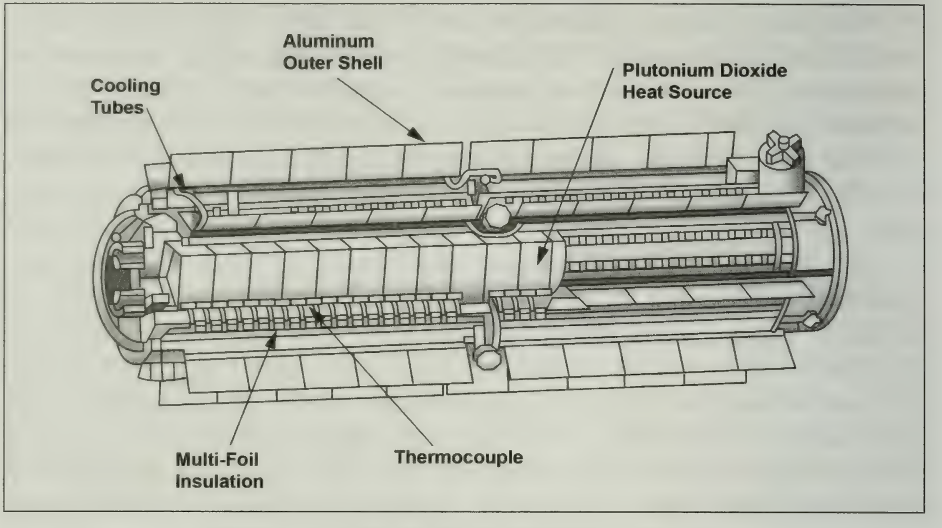

Figure 4–71. Radioisotope Thermoelectric Generator.

Cassini launched on October 15, 1997, on a journey to cover 3.5 billion kilometers (2.2 billion miles). Because of Cassini's large size, it could not be sent directly to Saturn on any available launch vehicle. Four gravity assists were required. Cassini's interplanetary trajectory took it by Venus twice, then past Earth and Jupiter. The spacecraft flew past Venus on April 26, 1998, at an altitude of 284 kilometers (176 miles) and on June 24, 1999, at 600 kilometers (370 miles) before swinging past Earth on August 18, 1999, at 1,171 kilometers (727 miles). The fourth and final gravity assist was from Jupiter on December 30, 2000, at an altitude of 9,723,890 kilometers (6,042,145 miles). This boosted Cassini the remaining distance to Saturn. The Huygens probe was bolted to Cassini.[329] Figure 4–72 shows Cassini's interplanetary trajectory.

Spacecraft and Instruments

The Cassini-Huygens spacecraft is the most highly instrumented and scientifically capable planetary spacecraft ever flown, equipped with a total of 18 instruments, 12 on the orbiter and 6 on the Huygens probe. Many of these sophisticated instruments are capable of multiple functions. The orbiter's instruments gather data for 27 diverse science investigations. Cassini's payload represents the technical efforts of 260 scientists from the United States and 17 European nations.

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[329] "Cassini-Huygens Saturn Arrival Press Kit," June 2004, p. 35, *http://www.nasa.gov/pdf/60116main_cassini-arrival.pdf* (accessed September 20, 2005).

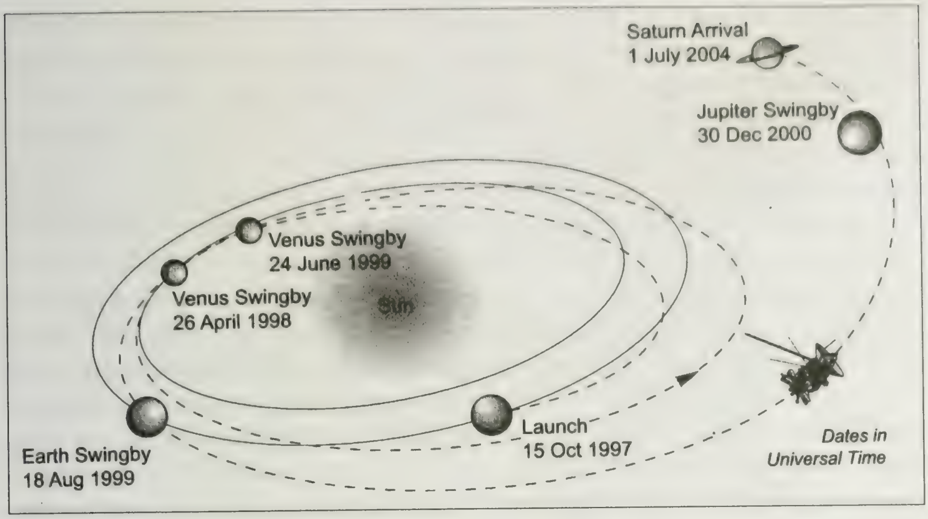

Figure 4–72. Cassini Interplanetary Trajectory.

The Huygens Probe system, built by an industrial consortium led by Aerospatiale, was supplied by the ESA. The system includes the probe that enters Titan's atmosphere after separation from the orbiter and probe support equipment (PSE) that remains attached to the orbiter.

The PSE includes a number of engineering subsystems and the electronics necessary to track the probe; recover the data gathered during its descent and process and deliver the data to the orbiter, which is then transmitted from the orbiter to the ground. The PSE consists of four electronic boxes aboard the orbiter—two probe support avionics, a receiver front end, and a receiver ultrastable oscillator; the spin eject device; and the harness (including the umbilical connector) that provides power, RF, and data links between the probe support avionics, probe, and orbiter.[330]

The probe itself consists of the Entry Assembly, which cocoons the Descent Module (DM) and provides orbiter attachment; umbilical separation and ejection; cruise and entry thermal protection; and entry deceleration control. The assembly is jettisoned after entry, releasing the DM. This module comprises an aluminum shell and inner structure containing the six instruments and all the experiments and probe support subsystems, including the parachute descent and spin control devices.

Cassini is one of the largest interplanetary spacecraft ever launched. Loaded with fuel and the Huygens probe and launch vehicle adapter, it weighed 5,712 kilograms (12,593 pounds) at launch. More than half the spacecraft's total mass was propellant. On the launch pad, the spacecraft stood 6.8 meters (22.3 feet) high and was 4 meters (13 feet) wide. Its magnetometer is mounted on an 11-meter (36-foot) boom extending from the spacecraft, and three other 10-meter (32-foot) antenna booms extend outward from the spacecraft. Multilayer blanketing material covering most of the spacecraft and its instrument housings protects Cassini against the extreme heat and cold of space. The blanketing material also maintains the needed room temperature operating environment for computers and other electronic systems. Layers of mylar in the blankets protect against micrometeoroids in interplanetary space.

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[330] "Huygens," European Space Agency, *http://huygens.esa.int/science-e/www/category/index.cfm?fcategoryid=4828* (accessed September 20, 2005).

The orbiter's main body consists of a lower equipment module, a propulsion module, and an upper equipment module. A fixed 4-meter (13-foot)-diameter high-gain antenna tops the stack. A remote sensing pallet containing cameras and other remote sensing instruments and a fields and particles pallet containing instruments that study magnetic fields and charged particles sit part way up the spacecraft. The whole spacecraft must be turned to point the instruments toward their targets, although three of the instruments can turn about one axis. The orbiter has 12 engineering subsystems governing spacecraft components and functions. A diagram of the spacecraft can be seen in figure 4–73. Mission details can be found in Table 4–79.

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Ongoing Planetary Missions

Four Pioneer and two Voyager spacecraft launched in previous decades continued operating into the 1990s.

Pioneer Missions

Pioneer 6 was the first of four NASA spacecraft designed to study interplanetary phenomena in space. Launched in 1965, Pioneer 6 continued to operate into the 1990s. By December 1990, Pioneer 6 had circled the Sun 29 times (traveling 24.8 billion kilometers) (15.4 billion miles) and had been operational for 20 years—a record for a deep space probe. Its original slated lifetime had been only six months. On December 15, 1996, the spacecraft's primary transmitter failed, but during a track on July 11, 1996, ground controllers switched on the backup transmitter. Of the spacecraft's six scientific instruments, two still continued to function (the plasma analyzer and cosmic-ray detector).

NASA maintained contact with the spacecraft once or twice each year. For example, 1 hour's worth of scientific data was collected on July 29 and December 15, 1995, (although the primary transmitter failed soon after that), and again on October 6, 1997, more than 30 years after launch. The probe's solar arrays continued to deteriorate, although the transmitters could be turned on at perihelion when the solar flux was strong enough to provide sufficient power. On December 8, 2000, to commemorate its 35th anniversary of operation, ground controllers established successful contact with the spacecraft for about 2 hours.[331] Two Pioneer planetary missions, Pioneer 10 and 11 launched in 1972 and 1973 continued to operate into the 1990s.

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[331] Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes, 1958–2000*, p. 52.

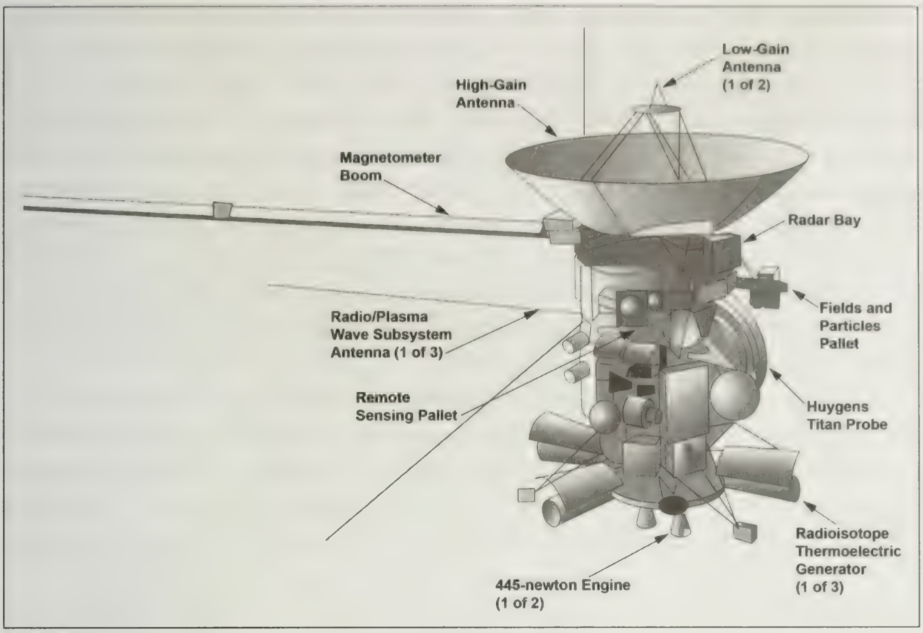
Low-Gain Antenna (1 of 2)
High-Gain Antenna
Magnetometer Boom
Radar Bay
Fields and Particles Pallet
Radio/Plasma Wave Subsystem Antenna (1 of 3)
Remote Sensing Pallet
Huygens Titan Probe
Radioisotope Thermoelectric Generator (1 of 3)
445-newton Engine (1 of 2)

Figure 4–73. Cassini Spacecraft.

Pioneer 10 attained a milestone on September 22, 1990, when it reached 50 times farther from the Sun than the Sun was from Earth—a distance of 50 astronomical units. The spacecraft had left our solar system planets behind on June 13, 1983. Pioneer 10 was the first spacecraft to cross the asteroid belt, fly by Jupiter, and return pictures and a description of the planet's magnetic field, interior structure and atmosphere, and the mass of its moons. The spacecraft's most important finding about the outer solar system was the extent of the Sun's heliosphere, originally thought to end at the orbit of Jupiter. But at almost 10 times farther away, Pioneer 10 was still within the solar heliosphere.[332]

Both Pioneer 10 and Pioneer 11 provided data to NASA scientists in 1989 allowing them to produce "celestial constants," the first "pure" measurements of the various kinds of background light in our solar system, galaxy, and universe. Scientists determined that background light from beyond the solar system was made up of approximately 82 percent light from faint stars. Most of the remaining light was galactic light diffused by dust and less than 0.6 percent originated beyond the galaxy. This data provided a benchmark in many areas of astronomy and physics. The work also provided a clue to the chemical composition of solar, galactic, and cosmic dust; gave an accurate measure of the Sun's position above the plane of the galaxy; and described how cosmic dust scattered light.[333]

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[332] "Pioneer 10 Marks New Epoch in Solar System Exploration," *NASA News* Release 90-125, September 18, 1990, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1990/90-125.txt* (accessed September 30, 2005).

[333] "Pioneers Make First Measurements of Interstellar Light," *NASA News* Release 89-186. December 27, 1989, *http://web.archive.org/web/20000613212615/spacelink.nasa.gov/NASA.News/NASA.News.Releases/Previous.News.Releases/89.News.Releases/89-12.News.Releases/89-12-17* (accessed August 16, 2005).

Pioneer 10 observed its 10th anniversary of leaving the solar system planets in June 1993. Five of its 11 instruments were still sending back data through the spacecraft's 7.5-watt radio signal. To that date, Pioneer 10 had transmitted more than 170 billion bits of science data and was continuing to transmit data daily.[334] Another major milestone occurred on March 2, 1997, when the spacecraft reached its 25th year in space 6.2 billion miles (10 billion kilometers) from Earth.[335] The Pioneer 10 science mission officially ended on March 31, 1997. Since that time, Pioneer 10's weak signal has been tracked by NASA's DSN as part of a new advanced-concept study of communication technology in support of NASA's future Interstellar Probe mission. Its last signal was received on January 22, 2003.[336]

Pioneer 11 crossed the orbit of Neptune on February 23, 1990, becoming the fourth spacecraft to leave the solar system at a distance of 2.8 billion miles (4.5 billion kilometers) from Earth. (At that date, because of Pluto's eccentric orbit, Neptune was farther from Earth than Pluto.) Pioneer 11 provided scientists with their closest view of Jupiter in December 1974, passing within 26,600 miles (42,800 kilometers) of its cloud tops. In 1979, Pioneer 11 approached within 13,000 miles (20,921 kilometers) of Saturn, taking the first close-up pictures of the planet. The spacecraft continued sending back limited data on the solar wind, magnetic field, and cosmic rays, but by September 1995, although two instruments were still operational, Pioneer 11 could no longer be maneuvered to point its antenna accurately at Earth. On September 30, after the spacecraft traveled beyond the orbit of Pluto and more than 4 billion miles (6.4 billion kilometers) from Earth into interstellar space, Pioneer 11 ceased daily communications with NASA as controllers terminated routine contact with the spacecraft. Controllers began using the DSN antennae to listen for the spacecraft's signal only about 2 hours every two to four weeks.[337] The last communication from Pioneer 11 was received in November 1995 when Earth moved out of view of the spacecraft's antenna. Both Pioneer 10 and Pioneer 11 carried a plaque for communicating with any intelligent species that might find the spacecraft (see Figure 4–74).

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[334] "Pioneer Celebrates 10 Years Beyond the Known Solar Planets," *NASA News* Release 93-110. June 11, 1993, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1993/93-110.txt* (accessed September 30, 2005).

[335] "Pioneer 10 Spacecraft Nears 25th Anniversary, End of Mission," *NASA News* Release 97-31, February 27, 1997, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1997/97-031.txt* (accessed September 30, 2005).

[336] "Pioneer 10 Spacecraft Sends Last Signal," *NASA News* Release 03-082, February 25, 2003, *http://www.nasa.gov/home/hqnews/2003/feb/HP_news_08082.html* (accessed September 30, 2005).

[337] "Pioneer 11 To End Operations After Epic Career," *NASA News* Release 95-163, September 29, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-163.txt* (accessed September 30, 2005).

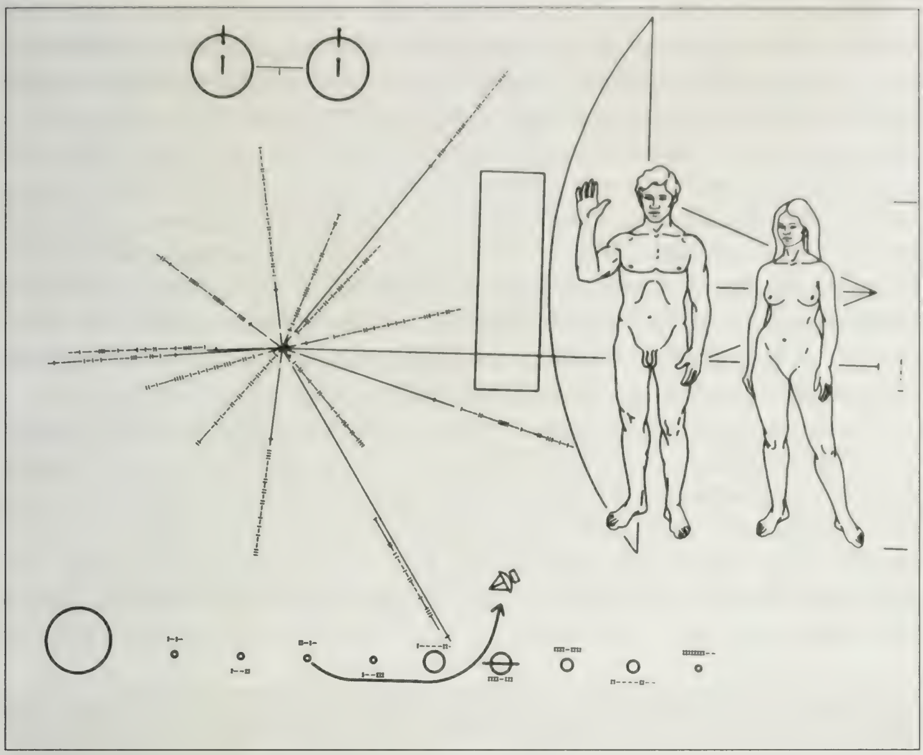

Figure 4–74. Pioneer 10 and Pioneer 11 carry this pictorial plaque. It was designed to show scientifically educated inhabitants of some other star system who might intercept it from where, and by what kind of beings, it came. The design was etched into a 6 inch by 9 inch (15 cm by 23 cm) gold-anodized aluminum plate and is attached to each spacecraft's antenna support struts in a position to help shield it from erosion by interstellar dust. (NASA Photo No. 72-H-192)

Pioneer Venus (Pioneer 12) was launched in 1978. Although its planned primary mission duration was only eight months, Pioneer 12 operated until October 1992. The spacecraft performed long-term observations of the Venusian atmosphere and surface features. Pioneer 12 returned global maps of the planet's clouds, atmosphere, and ionosphere; measurements of the atmosphere-solar wind interaction; and radar maps of 93 percent of the planet's surface. Additionally, the spacecraft used several opportunities to make systematic UV observations of several comets in the 1980s.[338]

Starting in September 1992, controllers used the remaining fuel in a series of maneuvers to keep raising periapsis altitude for as long as possible. On October 8, 1992, its fuel supply was exhausted, and the spacecraft plunged through the Venusian atmosphere as a flaming meteor.[339]

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[338] "Pioneer 12," Quicklook, Mission and Spacecraft Library, Jet Propulsion Laboratory, *http://samadhi.jpl.nasa.gov/msl/QuickLooks/pioneer12QL.html* (accessed September 9, 2005).

[339] "The Pioneer Missions," *http://spaceprojects.arc.nasa.gov/Space_Projects/pioneer/PNhist.html* (accessed September 9, 2005).

The spacecraft returned evidence for early oceans on Venus and gave new support for the presence of lightning on the planet, phenomena doubted by some scientists. Data showed that Venus, which had become hot and dry, once had 3.5 times as much water as thought earlier—enough to cover the entire surface between 25 feet (7.6 meters) and 75 feet (22.9 meters) deep. Data also suggested that, at Pioneer's lowest altitude of 80 miles (29 kilometers), "whistler" radio signals, believed generated by Venus's lightning, were the strongest ever detected. They were the same as the radio signals used in most lightning studies on Earth. Pioneer 12 penetrated 7 miles (11.3 kilometers) below the peak of Venus's ionosphere, which tended to block the radio signals. At that altitude, the magnetic fields that channeled the signals were the strongest ever seen on Venus's night side.

During a three-month period, Pioneer 12 provided data from 80 miles to 210 miles (129 kilometers to 338 kilometers) altitude. The spacecraft found the beginning of Venus's real, mixed atmosphere at 80 miles. Below 85 miles (137 kilometers), the spacecraft identified various waves and a four-day oscillation of Venus's atmosphere-top. The neutral atmosphere above 185 miles (298 kilometers) was more than 10 times denser and 1,800°F (982°C) hotter than thought.[340]

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Voyager

Voyager 1 and Voyager 2, identical spacecraft, were launched on September 5 and August 20, 1977, respectively. During the first 10 years of its mission, Voyager 1 encountered Jupiter and Saturn, scanned Saturn's primary moon Titan, and was flung by Saturn's gravity up out of the ecliptic plane. Voyager 2 followed Voyager 1 to Jupiter and Saturn, and then the spacecraft proceeded to Uranus and Neptune, using the gravity of each planet to boost it to the next.

As Voyager 2 approached Neptune, the spacecraft made several discoveries. Images from the spacecraft revealed three additional new moons, bringing the total number of known moons to six. The new moons occupied nearly circular and equatorial orbits around the planet. All moved in the same direction the planet rotated, making the large moon Triton, which occupied a retrograde orbit, even more of an oddity in the Neptune system. The three moons orbited at distances of about 32,300 miles (52,000 kilometers), 38,000 miles (61,155 kilometers), and 45,400 miles (73,000 kilometers) from the planet's center.

Neptune investigators also found two ring arcs, or partial rings, in images returned by Voyager 2. The two ring arcs were apparently associated with two of the new Neptunian moons found by Voyager. The ring arcs may be composed of debris associated with the moons or may be remnants of moons that were ground down or torn apart through collisions. Astronomers suspected the existence of such an irregular ring system around Neptune, but Voyager's photographs were the first evidence of their existence.

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[340] Peter Waller, "Pioneer Venus Orbiter Final Results Provide Evidence for Oceans and Lightning on Venus," *Astrogram*, Ames Research Center (April 2, 1993): 1.

Voyager found evidence of a magnetic field from intense radio emissions from Neptune. The intensity of the emissions indicated that Neptune's magnetic field was similar in intensity to the fields of Earth and Uranus. Voyager's cameras also captured a 5-mile (8-kilometer) high, geyser-like plume of dark material erupting from the surface of Triton. This was the first time that geyser-like phenomena were seen on any object in the solar system other than Earth since Voyager earlier discovered eight active geysers shooting sulfur above the surface of Jupiter's moon.

On August 25, 1989, Voyager 2 flew within 5,000 kilometers (3,000 miles) of Neptune, the closest encounter to the planet and the highlight of the spacecraft's "Grand Tour" of the outer planets. At the time, the planet was the most distant member of the solar system from the Sun. (Figure 4–75 shows an image of Neptune's rings.) Following its closest approach to Neptune, the spacecraft flew southward, below the ecliptic plane onto a course to interstellar space and the heliopause. Reflecting the Voyager's new transplanetary destinations, the extended project became known as the Voyager Interstellar Mission.

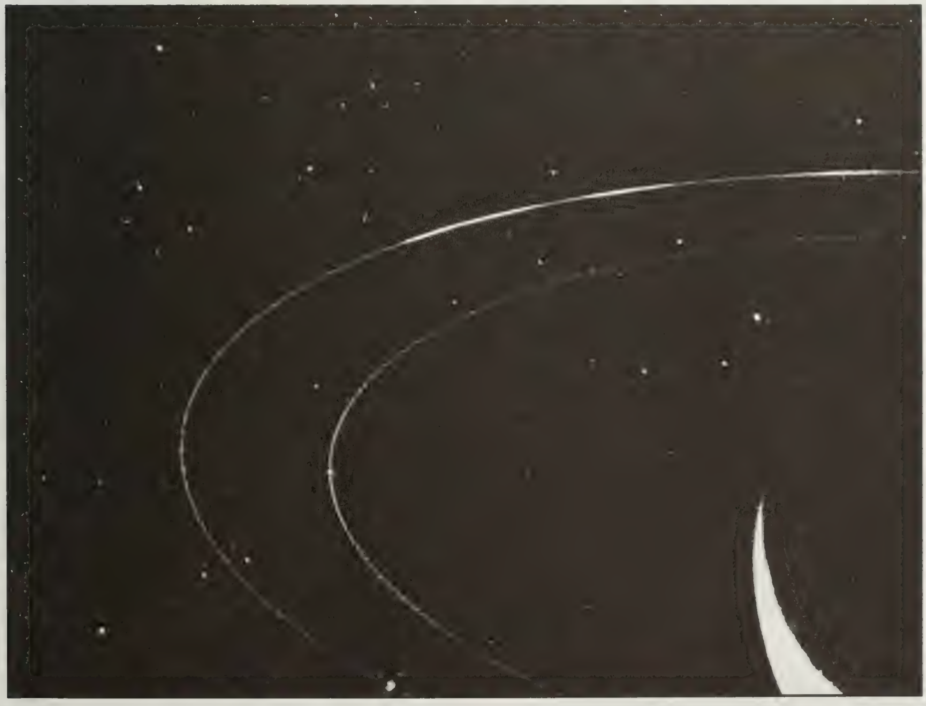

Figure 4–75. Voyager 2 acquired this image of Neptune's rings in its encounter of the planet in August 1989. In Neptune's outermost ring, 39,000 miles (62,764 kilometers) out from the planet, material mysteriously clumps into three arcs. (NASA-JPL Photo No. P35060)

On February 17, 1998, Voyager 1 became the most distant human-made object, reaching almost 70 times farther from the Sun than Earth. At a distance of 6.5 billion miles (10.4 billion kilometers) from Earth and traveling at a speed of 39,000 miles per hour (62,764 kilometers per hour) away from the Sun, the spacecraft outdistanced Pioneer 10 in their opposite journeys away from the Sun. At the same time, Voyager 2 was 5.1 billion miles (8.1 billion kilometers) from Earth, departing the solar system at a speed of 35,000 miles per hour (56,327 kilometers per hour).[341] Experts estimate that both spacecraft have enough electrical power to continue operating until about 2020.[342] Table 4–80 lists selected Voyager events.

Attached Shuttle Payload Bay Science Missions

With every Space Shuttle mission, NASA had a platform for performing scientific experiments. NASA used the Shuttle's microgravity environment for a variety of smaller experiments; small, self-contained payloads; and large experimental missions. Astronauts used the Shuttle's capabilities for investigations in atmospheric physics; Earth observation; space plasma physics; life sciences; materials science; astronomy; solar physics; and technology. Among these were the Spacelab missions and commercial investigations, such as those carried in SPACEHAB modules, which are described in the individual Shuttle mission tables in chapter 3. Attached space science missions are described more fully in this section.

In addition, the Space Shuttle launched and retrieved a number of small satellites; some were free-flying and others suspended at the end of the Shuttle's robot arm. They are described below.

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Astro-1

Astro-1 began in 1978 with an announcement of opportunity for instruments to travel aboard the Space Shuttle and use the unique capabilities of Spacelab. Three telescopes, the HUT, UIT, and WUPPE, evolved as a payload listed as OSS-3 through OSS-7. In 1982, the mission was renamed Astro. The WFC was added to the payload in 1984 to make detailed studies of Comet Halley, which was due to move through the inner solar system in the spring of 1986, the original Astro-1 launch date. The instruments were constructed, and the observatory had completed Spacelab integration and testing by January 1986. Astro-1, consisting of the HUT, UIT, WUPPE, and WFC, was ready for orbiter installation when the *Challenger* accident occurred, delaying future Space Shuttle missions. During the delay, the instruments were removed from Spacelab and stored. Periodic checks were made during storage and a number of parts were replaced.[343]

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[341] "Voyager 1 Now Most Distant Human-Made Object in Space," *NASA News* Release 98-30, February 13, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-030.txt* (accessed September 30, 2005).

[342] Mary Hardin, "Voyager 1 Now Most Distant Human-Made Object in Space," Jet Propulsion Laboratory, *Universe* 28 (February 20, 1998): 1, 3.

Also, because Comet Halley was no longer in position for detailed observation, the WFC was removed in the spring of 1987. In March 1988, the BBXRT was added to the Astro-1 payload. The addition allowed study of supernovae and other objects in x-ray and UV wavelengths.

Astro-1 was installed in *Columbia*'s payload bay on March 20, 1990, and launch occurred on December 2.[344] It was a dedicated Spacelab mission to conduct astronomical observations in the UV spectral regions. Its primary objectives were to obtain the following:

- Imagery in the spectral range from 1,200 angstroms to 3,100 angstroms (UIT)
- Spectrophotometry in the spectral region from 425 angstroms to 1,850 angstroms (HUT)
- Spectrapolarimetry from 1250 angstroms to 3,200 angstroms (WUPPE)
- X-ray data in the bandpass between 0.3 keV and 12 keV (BBXRT)

Astro-1 was the first Spacelab mission devoted to a single scientific discipline—astrophysics. It was an extremely productive science mission despite the loss of both data display units used for pointing the telescopes and operating experiments during the mission. The loss affected crew-aiming procedures and forced ground teams at Marshall Space Flight Center to aim the UV telescopes while the flight crew fine-tuned the telescopes's orientation. The returned data volume was less than half of that originally planned, and the science return was approximately 67 percent of the stated goals of the mission.[345]

Astro-1's UV and x-ray telescopes made 231 observations of 130 unique astronomical targets during a 10-day period, capturing the first views of many celestial objects in extremely short UV wavelengths, taking the first detailed UV photographs of many astronomical objects, and making the first extensive studies of UV polarization.[346] The instruments observed for a total of 143 hours. All three UV telescopes observed the Cygnus Loop, the remnant of an explosion some 40,000 years ago. Observations detected a much higher temperature and greater velocity of its shock wave than had been predicted. The telescopes also studied the Crab Nebula, a relatively young supernova remnant.

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[343] "Space Shuttle Mission STS-35 Press Kit," December 1990, p. 39, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_038_STS-035_Press_Kit.pdf* (accessed August 22, 2005). The IPS and other Spacelab facilities were needed for the HUT.

[344] "Space Shuttle Mission STS-35 Press Kit," December 1990.

[345] "Astro 1," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1* (accessed August 30, 2005).

[346] "Space Shuttle Mission STS-67 Press Kit," March 1995, p. 18, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_068_STS-067_Press_Kit.pdf* (accessed August 30, 2005).

The HUT, developed at The Johns Hopkins University, obtained spectra of significant examples of almost every major class of astronomical object, ranging from distant galaxies and quasars to stars, star clusters, and clouds of gas and dust in our own galaxy as well as observing familiar objects within our solar system. HUT scientists learned about conditions in the cores of active galaxies, obtaining evidence for a new path of stellar evolution for old stars residing in these galaxies. The telescope also found new evidence for a hot, gaseous halo surrounding the Milky Way galaxy. The HUT made several observations of Jupiter and its moon Io, studying the dynamic nature of their relationship. Scientists used the HUT's more detailed spectra to reinterpret data gathered by the Voyager spacecraft in the late 1970s.[347]

Astronomers used HUT data to study various diffuse nebulae in our galaxy. They learned about the characteristics of dust near hot stars and the speeds of shock waves produced by supernova explosions. Astronomers also gathered information on the chemical composition of this tenuous material in interstellar space. The HUT also observed a handful of binary star systems called cataclysmic variable stars, in which two stars are locked in very tight orbits about each other. Objects studied in our solar system included the plasma produced by events relating to Jupiter's magnetic field and Io. The HUT observed a comet as the last observation made on the mission.[348] The HUT obtained spectra of 77 individual celestial targets on Astro-1.[349]

The UIT, sponsored by NASA's Goddard Space Flight Center, obtained a large number of images, including clusters of young, hot massive stars; globular clusters containing old stars, some of which were unusually hot; spiral galaxies rich with star-forming activity; and smaller "irregular" galaxies that could experience sudden bursts of star formation.[350] The UV images picked out hot stars in late stages of evolution, where hydrogen had been depleted from the cores, and burning helium provided energy. By comparing photographs taken in different wavelengths, scientists could measure the temperature and brightness of individual stars. The UIT also identified rings of massive star formation in several galaxies, including thousands of individual hot stars in other galaxies for later study by the Hubble Space Telescope. The telescope also revealed that the shapes of galaxies seen in UV wavelengths were strikingly different from their familiar forms in visible light.[351] The UIT obtained 821 exposures of 66 targets.[352]

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[347] "Space Shuttle Mission STS-67 Press Kit," March 1995, p. 21, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_068_STS-067_Press_Kit.pdf* (accessed August 30, 2005).

[348] "Achievements of Astro-1," *http://praxis.pha.jhu.edu/astro1/astro1_summary.html* (accessed August 25, 2005).

[349] "Hopkins Ultraviolet Telescope (HUT)," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1&ex=2* (accessed August 30, 2005).

[350] "The Ultraviolet Imaging Telescope," *http://praxis.pha.jhu.edu/instruments/uit.html* (accessed August 25, 2005).

[351] "Space Shuttle Mission STS-67 Press Kit," March 1995, pp. 19–20, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_068_STS-067_Press_Kit.pdf* (accessed August 30, 2005).

[352] "Ultraviolet Imaging Telescope (UIT)," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1&ex=3* (accessed August 30, 2005).

The WUPPE, built at the University of Wisconsin, was a pioneering effort to explore polarization and photometry in the UV spectrum. The instrument measured polarization by splitting the beam of radiation entering the telescope into two perpendicular planes of polarization. The beams were then passed through a spectropolarimeter and focused on separate array detectors for photometric measurements. The WUPPE found that the amount of polarized light coming from these stars was less than was seen in visible light and less than expected in the UV, indicating that some of the UV polarized light was being removed by the gas in the disk around the star. The wavelengths in the UV where polarized light was missing told astronomers that there were apparently atoms of gaseous iron in the disks close to be stars (stars that were spinning very fast).

The WUPPE also used half a dozen bright stars to illuminate the interstellar medium, shedding new light on the chemical composition and physical nature of the dust between stars in the Milky Way. Surfaces of these dust grains were thought to provide a safe haven for the formation of molecules, clouds of which were the "womb" for the formation of each generation of new stars. Astro-1 observations revealed that some parts of the galaxy seem to have dust grains that might look like tiny hockey pucks, while other parts seem to have a mixture of several sizes, shapes, and kinds of dust grains. The WUPPE made 98 observations of 75 targets on Astro-1, eight of which were spectrum-only (no polarimetry).[353]

The flight of the BBXRT marked the first opportunity for performing x-ray observations over a broad energy range (0.3 keV–12 keV) with a moderate energy resolution (typically 90 eV and 150 eV at 1 keV and 6 keV, respectively). This energy resolution, coupled with an extremely low detector background, made the BBXRT a powerful tool for the study of continuum and line emission from cosmic sources. The observing program was designed to be an even mix of galactic and extragalactic targets, although the galactic center region was not available due to the time of year that the BBXRT was launched.

The BBXRT, designed and built at the Laboratory for High Energy Astrophysics at NASA's Goddard Space Flight Center, was in orbit for almost nine days. The detector system was powered for nearly the entire time, collecting source, background, or calibration data. The instrument behaved almost flawlessly on orbit. Although the BBXRT's observing efficiency was reduced due to problems in the spacecraft's pointing systems, it achieved a total of 185,000 seconds of observation time on cosmic x-ray sources. An additional 100,000 seconds of the total available observing time was usable for studies of the diffuse x-ray background. A total of 157 observations of 82 x-ray sources was achieved, with typical observation times ranging from 300 seconds to 3,000 seconds. See Table 4–81 for further details.

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[353] "Wisconsin Ultraviolet Photopolarimetry Experiment (WUPPE)," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=ASTRO-1&ex=1* (accessed August 30, 2005).

Astro-2

The Astro-2 mission launched on STS-67 on March 2, 1995, for a 16 1/2-day mission, nearly twice as long as Astro-1. The Astro-2 mission was a dedicated Spacelab mission to conduct astronomical observations in the UV spectral regions.

Astro-2 marked the second flight of the Astro-1 suite of science instruments as the three Astro-1 UV telescopes were reassembled to form the Astro-2 observatory. The BBXRT was not used on Astro-2. An improved HUT, the UIT, and the WUPPE were mounted on an improved IPS on a Spacelab pallet in *Endeavour*'s cargo bay. The IPS furnished a stable platform, kept the telescopes aligned, and provided various pointing and tracking capabilities to the telescopes. During Astro-1, the IPS had difficulty locking onto guide stars properly, forcing the crew to manually point the IPS and track targets. In general, the astronauts were able to provide pointing stability of about 2 arc seconds to 3 arc seconds or better. However, in "optical hold," the IPS should be able to achieve sub-arc-second stability. After the Astro-1 mission ended, a team extensively modified and tested the IPS software and made other improvements to ensure the IPS worked properly for Astro-2.[354]

A new feature for Astro-2 was "community involvement." As well as the scientists and engineers who developed the instruments, guest investigators also used the Astro-2 telescopes for their own observations. The addition of the guest investigator teams produced an even broader range of attempted observations and brought the total list of different science programs to 23.

The UIT and WUPPE did not change from Astro-1. The UIT's cameras imaged about two dozen large spiral galaxies for inclusion in an atlas of such galaxies and made the first UV images of the entire Moon. The telescope also studied the rare, hot stars that were 100 times as hot as the Sun; elliptical galaxies; and some of the faintest galaxies in the universe. Investigators were disappointed, upon developing UIT film, to learn that one of its two cameras had malfunctioned undetected on orbit, but an initial assessment showed that 80 percent of science objectives were still met.

The WUPPE measured photometry and polarization of UV radiation from astronomical objects, greatly expanding the database on UV spectropolarimetry. Targets for interstellar medium study included dust clouds in the Milky Way and the nearby galaxy, the Large Magellanic Cloud. The WUPPE also studied several types of stars, including Wolf-Rayet and Be stars, and capitalized on the opportunity to study three recently exploding novae.[355]

The HUT performed spectroscopy in the far UV region of the spectrum to identify the physical processes and chemical composition of a celestial object. Its science program for Astro-2 expanded on results from Astro-1 and also

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[354] "Space Shuttle Mission STS-67 Press Kit," March 1995, p. 27–30.

[355] "Space Shuttle Mission Chronology–STS-67," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-67.htm* (accessed August 30, 2005).

broke new ground. By observing more active galaxies, elliptical galaxies, cataclysmic variables, and nebulae, the Astro-2 HUT observations provided a broader understanding of the phenomena involved in these objects.

Improvements to the HUT made it three times more sensitive than on the Astro-1 mission. The HUT's increased sensitivity, along with increased observation time and technical improvements to the IPS, enabled HUT scientists to gather five times more data than they did during the Astro-1 mission. It obtained higher-quality spectra and observed objects too faint to see previously, permitting the pursuit of new science programs.[356] The HUT, considered a complement to the Hubble Space Telescope, made 385 science pointings at 260 unique astronomical targets during the mission, collecting enough data to meet its primary mission objective of detecting the presence of intergalactic helium, a telltale remnant of the Big Bang explosion that began the universe. The HUT also studied Io and the Venusian and Martian atmospheres and, in conjunction with the Hubble Space Telescope, took UV measurements of Jupiter's aurora.[357] The HUT's scientific achievements on Astro-2 are described in Table 4–82.

Diffuse X-ray Spectrometer

The University of Wisconsin–Madison built the DXS experiment, and it was flown as an attached payload on the January 1993 flight of STS-54. Its main scientific goal was to obtain spectra of the diffuse soft x-ray background. This dataset allowed researchers to learn about the region of space for several hundred light years around the solar system.

The experiment consisted of two identical instruments, each mounted to a 200-pound (91-kilogram) plate, attached to the side of the Shuttle bay. Each instrument consisted of a detector, its associated gas supply, and electronics. The two large-area Bragg crystal spectrometers covered the energy range from 0.15 keV to 0.28 keV. Each detector contained a curved panel of Bragg crystals mounted above a position-sensitive proportional counter. A spectrum would be dispersed across the counter, with all portions of the spectrum being measured simultaneously. This eliminated the problem in conventional Bragg spectrometers of false features being introduced by a time-varying background. Yet while all wavelengths were measured at the same time, the various wavelengths came from different directions in the sky. Thus, the spectrometers were rocked back and forth about an axis perpendicular to the dispersed direction to obtain complete spectral coverage along an arc of the sky.[358]

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[356] "The Astro-2 Mission," *http://praxis.pha.jhu.edu/astro2/astro2_mission.html* (accessed August 30, 2005).

[357] "Achievements of Astro-2," *http://praxis.pha.jhu.edu/astro2/astro2_achieve.html* (accessed August 30, 2005).

[358] "The Diffuse X-ray Spectrometer," *http://heasarc.gsfc.nasa.gov/docs/dxs/dxs_about.html* (accessed August 25, 2005).

Throughout the 80 orbit nights of DXS data collection time during the Shuttle mission, the orbiter was oriented so that the DXS detectors repeatedly scanned the same arc on the sky—within 10 degrees of the galactic plane from longitudes of 150 degrees to 300 degrees. The sky covered was divided into five distinct regions: Auriga, MonoGem, Puppis, Vela, and Crux.[359]

The DXS obtained the first high-resolution spectra of the diffuse soft x-ray background in the energy band from 0.15 keV to 0.28 keV (43 angstroms to 84 angstroms), measuring the arrival direction and wavelength of incident low-energy x-rays. From this information, the DXS scientists could determine the spectrum (brightness at each wavelength) of the diffuse soft x-ray background from each selected region of the sky. By analyzing these spectral features, scientists could identify the temperature, the ionization state, and the elements constituting this plasma. From this data, they could tell whether the plasma was young and heated in the last 100,000 years or old and heated millions of years ago. Previous experiments could not measure the spectrum of the diffuse soft x-ray background. With its spectral determination capability, the DXS made this type of measurement possible for the first time.

The DXS investigation was proposed and selected in response to a 1978 announcement of opportunity to conduct scientific investigations aboard the Space Shuttle. NASA selected DXS and four other astrophysics investigations, including three UV instruments and one x-ray telescope that flew in December 1990 on the STS-35/Astro-1 mission. All had scientific objectives and requirements that could be accomplished in a 5-day to 10-day Shuttle mission. The DXS was originally manifested to fly with the BBXRT on the second Shuttle High Energy Astrophysics Laboratory flight. In the remanifesting that followed the *Challenger* accident, the BBXRT flew on Astro-1, and the DXS moved to STS-54.[360] The DXS was part of the Goddard Space Flight Center Shuttle Payload of Opportunity Carrier system and a Hitchhiker payload.

The SPARTAN Program

The SPARTAN program provided a series of less costly, reusable, free-flying space platforms to perform various scientific studies. The program was conceived in the late 1970s to take advantage of the opportunity offered by the Space Shuttle to provide more observation time for the increasingly more sophisticated experiments than the 5 to 10 minutes allowed by sounding rocket flights. Its astrophysics experiments evolved from NASA's sounding rocket program.[361] SPARTANs carried a variety of scientific instruments and offered the scientific community the capability to conduct astrophysics investigations in space between the capabilities offered by small payloads remaining in the orbiter and larger satellites orbiting Earth for long periods of time.

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[359] "The Diffuse X-ray Spectrometer Shuttle Package," *http://heasarc.gsfc.nasa.gov/docs/dxs/dxs.html* (accessed August 25, 2005).

[360] "Space Shuttle Mission STS-54 Press Kit," January 1993, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_053_STS-054_Press_Kit.pdf* (accessed August 25, 2005).

[361] "Spartan 201-5," Payloads STS-95, *http://www.shuttlepresskit.com/STS-95/payload9.htm* (accessed August 25, 2005).

SPARTAN satellites were launched aboard the Space Shuttle and deployed from the orbiter, where they performed preprogrammed missions. Scientific data was collected during each mission and recorded using a tape recorder and, in many cases, film cameras. There was no command and control capability after deployment; batteries provided power, and attitude control was accomplished with pneumatic gas jets. The three-axis stabilized spacecraft weighed 1,300 kilograms (2,866 pounds) with 500 kilograms (1,102 pounds) allotted to experiments. Its operational mission usually lasted about 45 hours. At the end of its mission, the SPARTAN was retrieved by the orbiter and returned to Earth for recovery of the data, refurbishment, and preparation for future missions.[362]

The SPARTAN program's primary scientific missions related to solar physics. The SPARTAN spacecraft could also be programmed to conduct stellar astronomy; Earth fine pointing; spacecraft technology experiments and demonstrations; and microgravity science and technology experiments.

Two groups of SPARTAN science missions flew during the 1989–1998 decade. The SPARTAN 201 flew five times; the SPARTAN 204 flew one mission. Another SPARTAN, the SPARTAN 207, flew a technology mission. Table 4–83 lists Spartan 201 missions.

SPARTAN 201

SPARTAN 201 was a small, rectangular satellite performing remote sensing of the solar wind and the Sun's extremely hot corona to increase our knowledge of the Sun's effects on Earth. Its scientific objective was to probe the physics of solar wind acceleration by observing the hydrogen, proton, and electron temperatures and densities, as well as the solar-wind velocities, in a variety of coronal structures at locations from 1.5 solar radii to 3.5 solar radii from the Sun. The spacecraft consisted of a service module containing attitude control; thermal control; payload function control; power distribution systems; and an instrument carrier, a cylindrical container holding the SPARTAN spacecraft's two instruments. On the bottom of the spacecraft was the upper portion of the release/engage mechanism (REM). The lower half of the REM was attached to the spacecraft's payload bay support structure. The two halves of the REM mated to hold the spacecraft in place on the support structure and unlatch to allow the satellite to be deployed.

The pair of complementary instruments, the Ultraviolet Coronal Spectrometer, provided by the SAO at Harvard, and the White Light Coronograph, designed and built by the National Center for Atmospheric Research High Altitude Observatory, performed co-registered observations and measured emissions of the Sun's extended corona. The instruments were mated and co-aligned inside the SP201 Instrument Carrier, a 0.43-meter (1.4-foot)-diameter and 3-meter (9.8-foot)-long cylinder with an aperture door that was opened after the satellite's release from the Shuttle.[363] The spectrometer measured the velocities, temperatures, and densities of the coronal plasmas. The white-light coronograph measured the intensity and polarization of the electrons in the coronal white light.[364] Both of these instruments had been used in previous sounding rocket flights.

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[362] "Spartan 201-01," NSSDC Master Catalogue: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-023B* (accessed August 25, 2005).

SPARTAN 201-01 (Solar Physics)

SPARTAN 201-01 was launched aboard *Discovery* on mission STS-56. It was deployed three days after launch and retrieved two days later. The SPARTAN acquired more than 20 hours of coronal observations. The primary targets during the mission were north and south polar coronal holes, a southeast helmet streamer, and an active region above the west limb.

After landing at Kennedy Space Center, and removal from the orbiter, SPARTAN 201-01 was returned to Goddard Space Flight Center where the instruments were removed from the spacecraft. The UV coronal spectrometer was subsequently sent to the SAO for postflight calibration and preparation for Spartan 201-02.

SPARTAN 201-02 (Coordinated Observations–Ulysses)

SPARTAN 201-02 was launched from *Discovery* during the STS-64 mission on September 13, 1994 and retrieved on September 15.[365] The main goal of the mission was to observe the extended solar corona coincident with the passage of the Ulysses spacecraft over the south pole of the Sun. Flying 50 miles behind *Discovery*, SPARTAN 201-02 obtained high precision spectral line profiles of H I Lyman alpha. This data was used to determine proton kinetic temperature and outflow velocities in the regions where the solar wind detected by Ulysses originated. Data also indicated that the corona had changed as the solar minimum phase of the solar cycle was approached.[366]

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[363] "The Spartan 201 Carrier," *http://cfa-www.harvard.edu/cfa/spartan/* (accessed August 25, 2005).

[364] "Spartan Solar Studies (WLC, UVCS)," Experiments: STS-95, *http://www.shuttlepresskit.com/STS-95/experiment17.htm* (accessed August 25, 2005).

[365] *Aeronautics and Space Report of the President, Fiscal Year 1994 Activities* (Washington, DC: National Aeronautics and Space Administration, 1995), p. 74.

[366] "Spartan 201 Missions," *http://www.cfa.harvard.edu/cfa/spartan/history.html* (accessed August 25, 2005).

SPARTAN 201-03 (Coordinated Observations–Ulysses)

SPARTAN 201-03, launched from *Endeavour* on STS-69 in September 1995, was coordinated with the passage of the Ulysses spacecraft over the north solar pole. The primary targets for the Ultraviolet Coronal Spectrometer on this flight were the north coronal hole and the boundary regions between coronal holes and streamers.

The SPARTAN 201-03 science mission succeeded in obtaining a unique set of UV spectroscopy, visible polarized brightness observations, and coordinated Ulysses in situ measurements of solar wind.[367] By comparing the data collected by the SPARTAN's two telescopes and combining the observations from this mission, the previous SPARTAN mission, and from Ulysses and ground-based instruments, scientists gained a much more complete picture of the origin of the solar wind. The coordinated results provided new insight into the unknown source of energy heating the solar corona and accelerating the solar wind particles. No previous mission had focused specifically on these fundamental questions.[368]

SPARTAN 201-04 (Calibration Flight–SOHO)

This SPARTAN mission developed problems soon after deployment from STS-87 in November 1997. After it was released from *Columbia*, the satellite failed to perform a pirouette maneuver because of an incomplete initialization sequence. The spacecraft was sent into a spin when *Columbia*'s robotic arm bumped it during a retrieval attempt.

After spacewalking astronauts recaptured the free flyer four days after deployment, NASA was cautiously optimistic that the flyer could be deployed for a shortened mission. The mission had to be cancelled because *Columbia* would not have had enough propellant for the rendezvous and capture activities.

Postflight testing and review of data tapes at Kennedy Space Center in January 1988 confirmed that the SPARTAN satellite was healthy and had performed as expected in off-nominal conditions. All flight data correlated well with in-flight predictions and assessments.[369] (Figure 4–76 shows the SPARTAN held by the Shuttle's robotic arm.)

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[367] "Spartan 201 Missions."

[368] "Spartan 201-5," Payloads: STS-95, *http://www.shuttlepresskit.com/STS-95/payload9.htm* (accessed August 25, 2005).

[369] "Spartan 201-05 To Fly on STS-95," *NASA Facts*, Goddard Space Flight Center, FS-1998,09-022-GSFC, *http://www.gsfc.nasa.gov/gsfc/service/gallery/fact_sheets/spacesci/spartan.pdf* (accessed August 25, 2005).

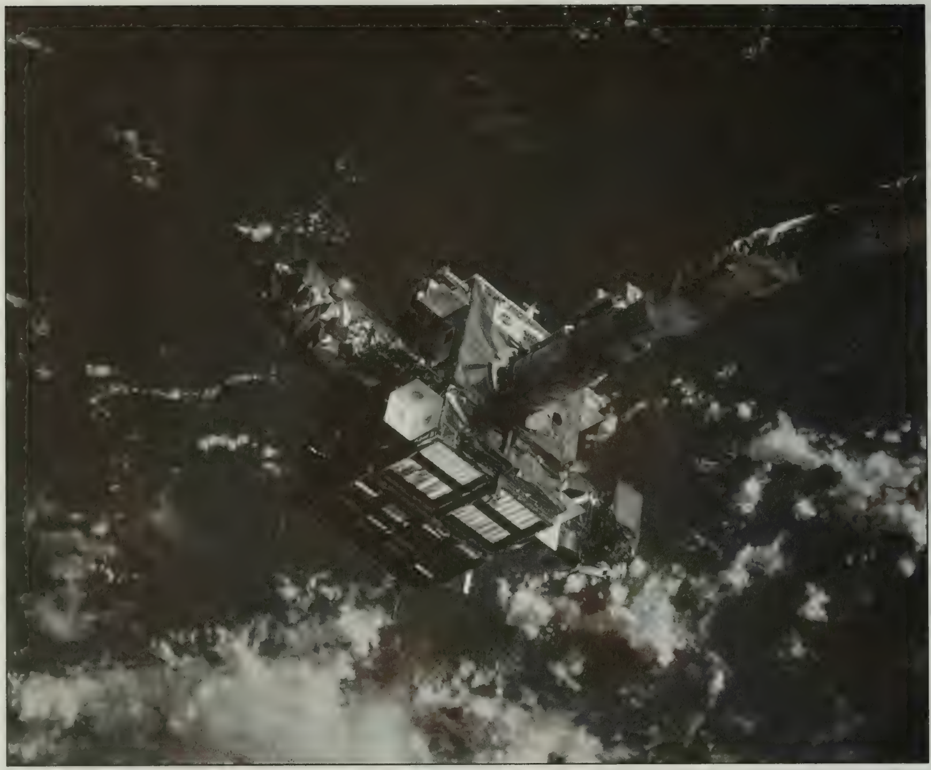

Figure 4–76. The SPARTAN 201-04 Satellite, held in the grasp of the Space Shuttle Columbia*'s Remote Manipulator System Arm, is backdropped over white clouds and blue waters of the Pacific Ocean. The photo was taken during STS-87. (NASA Photo No. STS087-706-020)*

SPARTAN 201-05 (Calibration Flight–SOHO)

SPARTAN 201-05 was a reflight of the STS-87 SPARTAN 201-04 mission, which had developed problems shortly after being deployed from the Shuttle. This flight, on STS-95, was coordinated with observations made by SOHO, an international mission between the ESA and NASA. In particular, the SPARTAN Ultraviolet Coronal Spectrometer was used to determine the instrumental profile of the H I Lyman alpha line for SOHO's Ultraviolet Coronal Spectrometer.

The SPARTAN spacecraft spent two days gathering data before being retrieved and stored on the Shuttle once more. On this mission, astronauts tested a device called the Video Guidance Sensor, part of an automated docking system being prepared for use on the ISS. This laser system provided precise measurements of how far away the Shuttle was from a target and how fast it was moving toward or away from the target. Before grappling SPARTAN, *Discovery* backed away from the satellite to test the maximum range capability of the guidance system.

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On the next day of the mission, astronauts again removed SPARTAN from its payload bay cradle for several hours of data collection. Cameras were pointed at a series of targets on the SPARTAN and on the Shuttle cargo bay to test the Orbiter Space Vision System, which used remote camera views to give a robot arm operator the ability to see areas outside the direct viewing area. The system was to be used extensively during the next Space Shuttle flight to help the robot arm join the first two ISS modules. Following the Orbiter Space Vision System test, an astronaut used the Video Guidance System to assist in rebirthing the SPARTAN in the payload bay.[370]

SPARTAN 204 Mission: UV Astronomy (Stellar)

SPARTAN 204 was flown on one Space Shuttle mission, STS-63, in February 1995. The crew lifted it from its support structure in the *Discovery* payload bay with the orbiter remote manipulator system arm on flight day two (February 4), where it remained suspended for observation of orbiter glow phenomenon and thruster jet firings. SPARTAN 204 was released from *Discovery* on February 7 to carry out about 40 hours of observations of galactic dust clouds using its FUVIS; it was retrieved February 9. The FUVIS was provided by the Naval Research Laboratory and sponsored by the Department of Defense Space Test Program.[371]

The instrument studied celestial targets in the interstellar medium, the gas and dust that filled the space between the stars and the material from which new stars and planets were formed. It obtained far UV spectroscopy of diffuse sources, both natural and human-made. The data acquired from natural sources, such as diffuse nebulae and the galactic background, provided information on interstellar gas and dust. Data acquired from sources such as Shuttle surface glow and plume emissions from its reaction control system thrusters provided information on the effect of these objects traveling through space. A better understanding of these effects might provide a way to detect and track ballistic and orbiting vehicles.[372]

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[370] "STS-95 Day 6 Highlights," *http://science.ksc.nasa.gov/shuttle/missions/sts-95/sts-95-day-06-highlights.html* and *http://science.ksc.nasa.gov/shuttle/missions/sts-95/sts-95-day-07-highlights.html* (accessed August 25, 2005).

[371] "Spartan 204," NSSDC Master Catalogue, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1995-004B* (accessed August 26, 2005). Also *http://science.ksc.nasa.gov/shuttle/missions/sts-63/mission-sts-63.html* (accessed August 26, 2005). The NSSDC Master Catalogue gives the date of Spartan deployment as February 6. The Mission Chronology gives it as Flight Day 2: February 7, which is used here.

[372] "Spartan," NASA Science, *http://science.hq.nasa.gov/missions/satellite_66.htm* (accessed August 25, 2005). Also "Space Shuttle Mission Chronology: STS-63," *http://www-pao.ksc.nasa.gov/kscpao/chron/sts-63.htm* (accessed August 25, 2005).

ASTRO-Shuttle Pallet Satellite Missions

The ASTRO-SPAS program was a joint German-U.S. endeavor based on a memorandum of understanding between NASA and the German Space Agency, DARA. The ASTRO-SPAS was a German-built spacecraft designed for launch, deployment, and retrieval from the Space Shuttle. Once deployed by the Shuttle's RMS, the SPAS operated quasi-autonomously for several days in the Shuttle vicinity (see figure 4–77). After completion of the free-flight phase, the RMS retrieved the spacecraft, and the Shuttle returned it to Earth. The program was very cost efficient, owing to the versatility and the retrievability of the carrier.

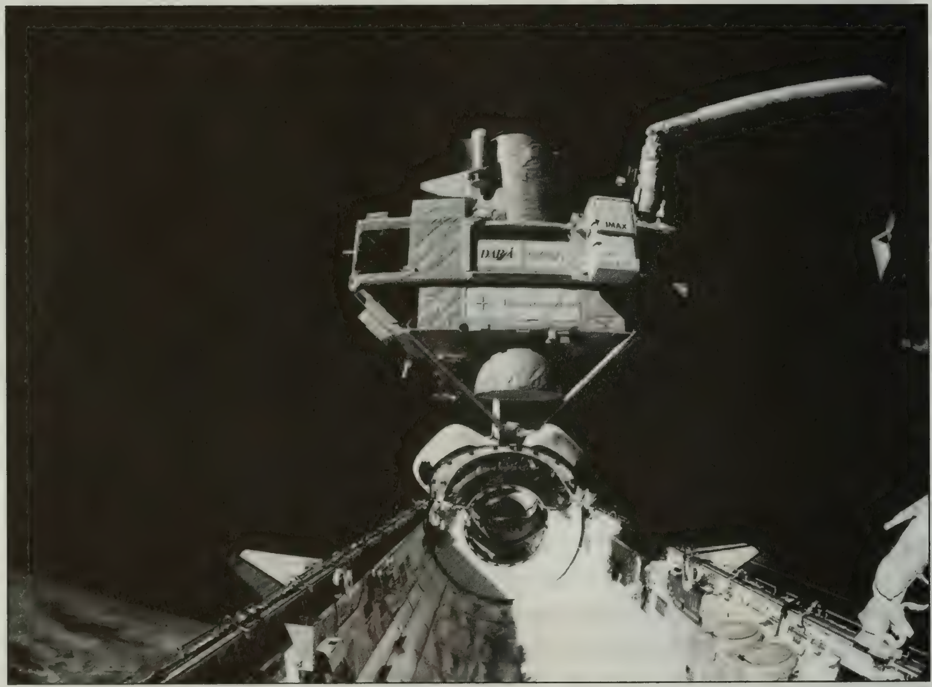

Figure 4–77. ORFEUS-SPAS II at the Robot Arm of Space Shuttle Columbia. *(Institut für Astronomie und Astrophysik)*

The ASTRO-SPAS spacecraft could trace its heritage back to the SPAS-01 satellite of June 1983, the SPAS-01A of February 1984, and the Infrared Background Signature Survey, an experiment performed on STS-39 in April 1991. The SPAS versatility permitted it to support a wide range of scientific applications, including two infrared-sensing ORFEUS-SPAS missions and two CRISTA-SPAS Earth science missions that mapped trace gases in Earth's middle and upper atmosphere.[373]

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[373] "Space Shuttle Mission STS-80 Press Kit," November 1996, p.18, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_080_STS-080_press-Kit.pdf* (accessed August 26, 2005).

The spacecraft's structure subsystem was a truss framework made of carbon fiber tubes with titanium nodes. Its standardized, interchangeable equipment support panels also served as mounting plates for subsystem and payload components. This resulted in a very rigid, stable, lightweight optical platform. The spacecraft was equipped with extensive on-board facilities and resources for scientific payloads. Power for all spacecraft and payload systems was provided by a powerful space-qualified lithium-sulfite ($LISO_2$) battery pack and its power distribution system. Thermal regulation was passive, accomplished with multilayer insulation blankets. Data was recorded through an on-board processor and data tape recorder, and it was stored for postflight analysis. Precise attitude control was achieved by a three-axis stabilized cold gas system combined with a star tracker and a specially developed spaceborne GPS receiver. Interactive command and control was provided by an S-band link via the Extended Range Payload Communications Link on the Shuttle. The Extended Range Payload Communications Link communicated with the ground via the Ku system. The spacecraft had a grapple fixture for deploy and rebirth with power and data interfaces for spacecraft checkout while attached to the RMS.[374]

ORFEUS-SPAS Missions

The first of two ORFEUS-SPAS astrophysics missions flew on STS-51 in September 1993. The second flew on STS-80 in November/December 1996. Both missions used the same satellite and science instruments and had similar scientific objectives (see Table 4–84). Both performed astronomical observations at very short wavelengths, specifically the far UV (90 nanometers to 125 nanometers) and EUV (40 nanometers to 90 nanometers) wavelengths. German and U.S. research institutions provided the ORFEUS-SPAS science payload, which was funded through the German Space Agency, DARA, and NASA.

The missions observed some of the coldest (several degrees above absolute zero) and hottest (more than 1 million degrees) matter in our galaxy. The core payload was the 1-meter-diameter UV telescope with the FUV Echelle spectrograph and the EUV spectrograph built into the telescope.[375] The Astronomical Institute, Tübingen, together with Landessternwarte Heidelberg Research Group, developed the design and construction of the telescope and FUV spectrograph.[376] The telescope had a 2.4-meter (7.9-foot) focal length. An iridium coating on the primary mirror improved its reflectivity for UV wavelengths. The carbon fiber epoxy compound tube structure provided essential stability against mechanical and thermal load deformations.

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[374] "ORFEUS-SPAS" Pre-Launch Mission Operation Report (no report number), p. 9 (NASA History Office Electronic Document 30982).

[375] The FUV spectrometer also was called the Tubingen Ultraviolet Echelle Spectrometer (TUES). The EUV spectrometer also was called the Berkeley Extreme and Far-UV Spectrometer (BEFS). "ORFEUS-SPAS I," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1993-058C.html* (accessed August 29, 2005).

[376] "ORFEUS-SPAS" Pre-Launch Mission Operation Report (no report number), p. 10 (NASA History Office Electronic Document 30982).

A secondary, but highly complementary, payload was the IMAPS. In addition to the astronomy payloads, ORFEUS-SPAS carried the SESAM, and ORFEUS-SPAS I carried the RICS.

The EUV spectrograph was directly exposed to light reflected off the main mirror. It covered the spectral range from 40 nanometers to 115 nanometers, offering a resolution of about 5,000 over the whole bandwidth. To achieve this unprecedented resolution over such a wide bandwidth, a completely new design was used that produced high-quality spectra. The EUV spectrograph was built by the Space Astrophysics Group at the University of California, Berkeley.

The FUV Echelle spectrograph was operated alternately with the EUV spectrograph by flipping a mirror into the beam reflected off the primary mirror. The FUV spectrograph covered the wavelength range from 90 nanometers to 125 nanometers and provided a spectral resolution on the order of 10,000.

The IMAPS was a separate instrument attached to the SPAS framework and operated independently of the ORFEUS telescope spectrographs. The IMAPS covered the 95-nanometer to 115-nanometer band. This wavelength was very important for studying principal constituents of the medium. The IMAPS also had a very high spectral resolving power, permitting it to disentangle the Doppler shifts of parcels of gas moving very slowly with respect to each other.[377] The IMAPS had been successfully flown on several sounding rocket missions. The IMAPS was operated for about one day during the ORFEUS-SPAS I mission and for more than two days during the ORFEUS-SPAS II mission. During that time it observed the brightest galactic objects at extremely high resolutions. This resolution allowed study of fine structures in interstellar gas lines.

The SESAM experiment was a passive carrier for state-of-the-art optical surfaces and potential future detector materials. The SESAM investigated the effects of the space environment on materials and surfaces in different phases of a Space Shuttle mission, including launch, orbit, and reentry into Earth's atmosphere. A number of different optical coats were exposed for various lengths of time during the mission and then analyzed postflight for degradation in reflectivity. Data from this experiment was to be used in the planning and use of optical coatings for future flights.

The RICS aboard ORFEUS-SPAS I was a modified IMAX cargo bay camera mounted to the ORFEUS-SPAS. The RICS took footage of the orbiter during deployment and retrieval for a motion picture. The system was enclosed in a container to protect it from contamination and provide a controlled environment for the camera and film. The container's door opened for filming operations. At the same time, RMS operations and the ORFEUS-SPAS satellite was filmed by another IMAX camera aboard the Shuttle.

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[377] "ORFEUS-SPAS" Pre-Launch Mission Operation Report (no report number), p. 12 (NASA History Office Electronic Document 30982).

The RICS did not give the Payload Operations Center on the ground or the crew the ability to view scenes being filmed in real-time. Therefore, an EVA Maneuvering Unit Television (EMU-TV), a video camera with a transmitter and associated electronics, was mounted to the ORFEUS-SPAS. Its FOV was co-aligned with the RICS, so viewers on the orbiter and on Earth saw the same scene seen by the RICS. Figure 4–78 shows the ORFEUS-SPAS I configuration.

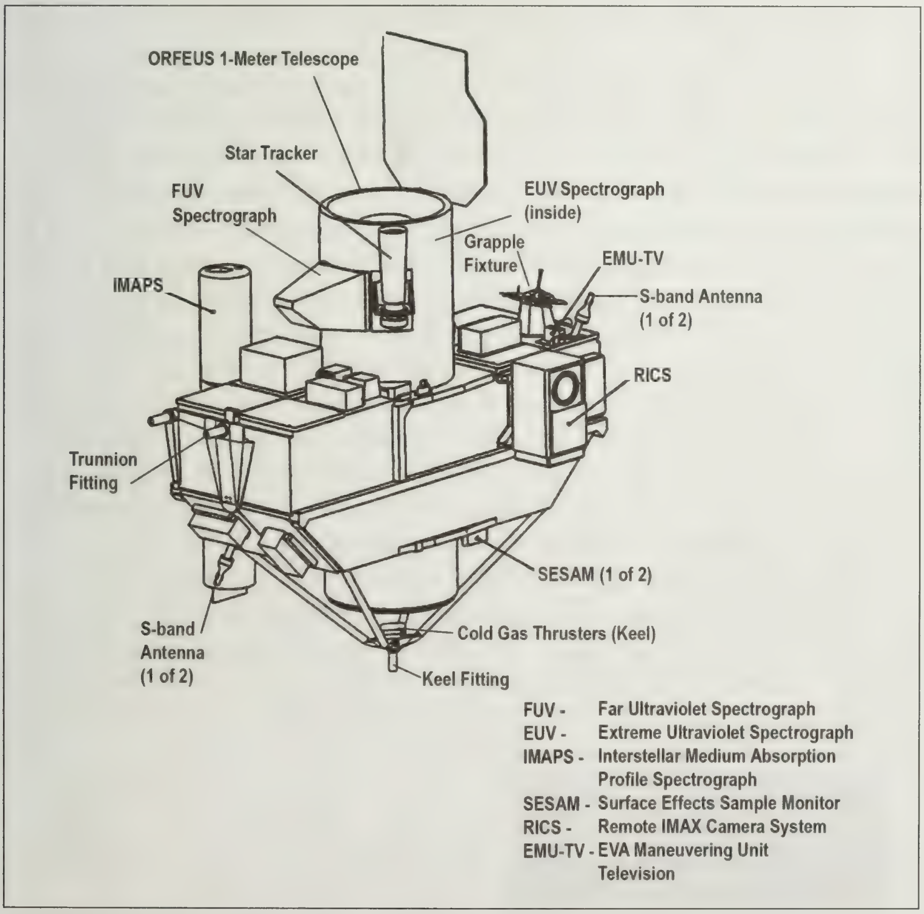
ORFEUS 1-Meter Telescope
Star Tracker
FUV Spectrograph
EUV Spectrograph (inside)
Grapple Fixture
EMU-TV
S-band Antenna (1 of 2)
IMAPS
RICS
Trunnion Fitting
SESAM (1 of 2)
S-band Antenna (1 of 2)
Cold Gas Thrusters (Keel)
Keel Fitting
FUV - Far Ultraviolet Spectrograph
EUV - Extreme Ultraviolet Spectrograph
IMAPS - Interstellar Medium Absorption Profile Spectrograph
SESAM - Surface Effects Sample Monitor
RICS - Remote IMAX Camera System
EMU-TV - EVA Maneuvering Unit Television

Figure 4–78. ORFEUS-SPAS I Configuration.

The ORFEUS-SPAS I mission provided valuable information in a largely unexplored region of the electromagnetic spectrum. The mission provided information on the details of the structure and dynamics of interstellar gas clouds and insight into how molecular hydrogen was created in interstellar space. The mission also studied neutral and ionized gas in the interstellar medium from the local solar neighborhood out to the distant halo of our galaxy. ORFEUS-SPAS I obtained spectra of a very diverse group of important astrophysical objects, including a compact interacting binary star with an enormous magnetic field, three hot white dwarf stars, and the distant active galaxy PKS2155-304.[378] The FUV spectrograph failed to record scientifically usable data during this mission. The EUV spectrograph obtained far-UV spectra of about 75 objects. The IMAPS returned approximately 600 spectral images of 10 targets.[379]

The ORFEUS-SPAS II mission took advantage of improved instrument performance and met the need for additional observation time.[380] It made half the observing time during the mission available to the general science community. Including the instrument teams, the ORFEUS-SPAS II mission had more than 40 research teams worldwide receiving and analyzing data from the mission. The mission acquired spectra of numerous celestial objects during 14 days of observations. The mission achieved an efficiency of 62.5 percent for all instruments. Unlike the first ORFEUS-SPAS mission when the FUV spectrograph did not record any scientifically usable data, the spectrometer operated successfully during this mission, returning about 239 spectra of 62 targets. The EUV spectrograph obtained far-UV spectra of about 105 objects, and the IMAPS returned approximately 3,900 spectra of about 29 targets.[381]

This mission also carried the Student Experiment on ASTRO-SPAS (SEAS). Students from the German high school of Ottobrunn built this electrolysis experiment consisting of eight experiment chambers containing various metal salt solutions and two electrodes. Metal "trees" of different shapes could grow on one electrode. Photographs taken of the process during the mission were compared with those of identical experiments conducted on the ground under the full effects of Earth's gravity.

The German Space Agency, DARA, developed an innovative educational program for students in 170 German high schools teaching astronomy, physics, and computer science. The classes were designed to prepare the students to use ORFEUS-SPAS data in their study of general astronomy, the life and death of stars, and stellar spectral analysis. The classes also prepared them to work with online satellite data.[382]

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[378] "Space Shuttle Mission STS-80 Press Kit," November 1996, pp. 15–16, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_080_STS-080_press-Kit.pdf* (accessed August 26, 2005),

[379] "ORFEUS-SPAS I," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1993-058C.html*. Also "ORFEUS-SPAS Tubingen Ultraviolet Echelle Spectrometer (TUES)," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-058C&ex=1*, "ORFEUS-SPAS, Berkeley Extreme and Far-UV Spectrometer (BEFS)," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-058C&ex=2*, and "ORFEUS-SPAS, Interstellar Medium Absorption Profile Spectrograph (IMAPS)" *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1993-058C&ex=3* (accessed August 29, 2005).

[380] "ORFEUS-SPAS II," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1996-065B.html* (accessed August 29, 2005).

[381] "ORFEUS-SPAS II," NSSDC Master Catalog: Spacecraft.

[382] "Space Shuttle Mission STS-80 Press Kit," November 1996, p. 17, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_080_STS-080_press-Kit.pdf* (accessed August 26, 2005).

Table 4–1. Space Science Launched Missions (1989–1998)

Launch Date	Mission	Objectives	Discipline	Remarks
May 4, 1989	Magellan	To place a satellite carrying a radar sensor into orbit around Venus to obtain data on the planet's surface	Planetary	Launched from Space Shuttle STS-30/*Atlantis*
October 18, 1989	Galileo	To launch a spacecraft into successful trajectory toward Jupiter to allow close-range studies over a period of two years	Planetary	Launched from Space Shuttle STS-34/*Atlantis*
November 18, 1989	Cosmic Background Explorer (COBE)	To launch a satellite to enable it to measure diffuse infrared radiation (cosmic background)	Astrophysics	Launched using the last NASA-owned Delta
April 25, 1990	Hubble Space Telescope	To perform a variety of astronomical observations as a long-term (15-year) international observatory with many different scientific goals and observational modes	Astrophysics	Launched from STS-31/*Discovery*; joint mission with the ESA
June 1, 1990	Roentgen Satellite (ROSAT)	To conduct an all-sky survey for six months using imaging telescopes to measure positions of x-ray and EUV sources while obtaining fluxes and spectral information	Astrophysics	International cooperative satellite with Germany and the United Kingdom; launched by the United States
July 25, 1990	Combined Release and Radiation Effects Satellite (CRRES)	To launch satellite into a highly elliptical geosynchronous transfer orbit to enable performance of active chemical release experiments in the ionosphere and magnetosphere	Space physics	A joint NASA–U.S. Air Force payload launched by the first commercial Atlas launch vehicle

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Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
October 6, 1990	Ulysses	To investigate properties of the solar wind; the structure of the Sun-wind interface; the heliospheric magnetic field; solar radio bursts and plasma waves; solar x-rays; solar and galactic cosmic rays; and interstellar and interplanetary neutral gas and dust	Solar physics	Deployed by Space Shuttle STS-41/*Discovery*; joint NASA-ESA mission
April 7, 1991	Compton Gamma Ray Observatory (CGRO)	To measure gamma radiation covering most of the celestial sphere and explore the fundamental physical processes powering it	Astrophysics	The second "Great Observatory"; deployed from Space Shuttle STS-37/*Atlantis*; a NASA cooperative program with Germany, with co-investigator support from the Netherlands, ESA, the United Kingdom, and the United States
August 30, 1991	Yohkoh/Solar-A	To study explosive energy releases from the Sun and identify the conditions preceding these energy releases so they can be predicted	Solar physics	Japanese mission (NASA and Japan jointly provided the Soft-X-ray Telescope); launched by Japan
June 7, 1992	Extreme Ultraviolet Explorer (EUVE)	To launch a satellite to make both spectroscopic and wideband observations across the entire EUV spectrum	Astrophysics	Reentered Earth's atmosphere over central Egypt on January 30, 2002, in a planned mission termination; burned up in the atmosphere

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
July 3, 1992	Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX)	To launch the first spacecraft in a new series of Small Explorers designed to investigate anomalous cosmic rays, galactic cosmic rays in the vicinity of Earth, solar energetic particles, and other space physics phenomena	Space physics	First Small Explorer mission; carried scientific instruments from the United States and Germany
July 24, 1992	Geotail	To investigate the geomagnetic tail region of the magnetosphere	Space physics	Japanese satellite launched by the U.S., part of the Global Geospace Science (GGS) program
September 25, 1992	Mars Observer	To study the geology, geophysics, and climate from a Mars orbit	Planetary	Successful launch but contact was lost before entering Mars orbit
February 20, 1993	Advanced Satellite for Cosmology and Astrophysics (ASCA) (originally called Astro-D)	To conduct x-ray spectroscopy of astrophysical plasmas, especially the analysis of discrete features such as emission lines and absorption edges	Astrophysics	Japanese mission launched by Japan; carried part of a U.S. payload; also called Asuka
January 25, 1994	Clementine	To test in space 23 advanced technologies for high-tech, lightweight missile defense; to provide images of the surface of the Moon	Technology demonstrator/ planetary	Joint DOD-NASA mission; DOD launch
November 1, 1994	Wind	To provide comprehensive measurements of radio and plasma wave phenomena occurring in the solar wind upstream of Earth's magnetosphere and in key regions of the magnetosphere from Lagrangian L1 orbit[a]	Space physics	Part of the International Solar-Terrestrial Physics (ISTP) program; GGS mission

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Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
December 2, 1995	Solar and Heliospheric Observatory (SOHO)	To study the Sun's internal structure by observing velocity oscillations and radiance variations and to look at the physical processes that form and heat the Sun's corona and that give rise to the solar wind from Lagrangian L1 orbit	Space physics	ESA-NASA mission; part of the International Solar-Terrestrial Physics (ISTP) program
December 30, 1995	Rossi X-ray Timing Explorer (RXTE)	To study the structure and dynamics of compact x-ray sources; including accreting neutron stars; white dwarfs; black holes in our galaxy; and compact, massive objects thought to be present in the nuclei of active galaxies	Astrophysics	Was the last large Explorer mission
February 17, 1996	Near Earth Asteroid Rendezvous (NEAR)	To perform multiple asteroid flybys and rendezvous with the asteroid Eros and gather data on its composition and physical properties	Planetary	First mission flown under NASA's Discovery Program
February 24, 1996	Polar	To perform multi-wavelength imaging of the aurora, measuring the entry of plasma into the polar magnetosphere and the geomagnetic tail, the flow of plasma to and from the ionosphere, and the deposition of particle energy in the ionosphere and upper atmosphere	Space physics	Part of GGS program and ISTP program

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
April 30, 1996	Beppo-SAX	To observe x-ray sources from 0.1 keV to 300 keV across large regions of the sky; to monitor large regions of the sky with a resolution of 5 arc minutes in the range 2 keV to 30 keV to study long-term variability of sources down to 1 mCrab and detect x-ray transient phenomena[b]	Astrophysics	Italian/Dutch celestial x-ray monitoring telescope; NASA provided launch vehicle, launch site, and data archiving
August 21, 1996	Fast Auroral Snapshot Explorer (FAST)	To investigate the plasma physics of the auroral phenomena occurring around both of Earth's poles	Space physics	Part of ISTP program
November 4, 1996	High-Energy Transient Experiment (HETE); Scientific Applications Satellite-B (SAC-B)	HETE: To carry out the first multi-wavelength study of gamma-ray bursts with UV, x-ray, and gamma-ray instruments; SAC-B: To study solar physics and astrophysics through the examination of solar flares, gamma-ray burst sources, and the diffuse soft x-ray cosmic background	Astrophysics	Argentinian mission launched by U.S.; Unsuccessful due to launch vehicle failure
November 7, 1996	Mars Global Surveyor	To orbit Mars during a two-year period and collect data on the Martian surface morphology; topography; composition; gravity; atmospheric dynamics; and magnetic field	Planetary	Designed as a rapid. low-cost recovery of the unsuccessful Mars Observer mission objectives
November 16, 1996	Mars '96 (Mars 8)	To land on Mars and investigate the evolution of its atmosphere, surface, and interior	Planetary	Russian mission launched from Russia with U.S. instrument on board; failed on launch

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Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
December 4, 1996	Mars Pathfinder	To demonstrate the feasibility of low-cost landings on Mars and explore the Martian surface	Planetary	Second NASA Discovery mission
August 25, 1997	Advanced Composition Explorer (ACE)	To determine and compare the isotopic and elemental composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and Galactic matter from the Lagrangian L1 orbit	Space physics	Began from an unsolicited proposal
October 15, 1997	Cassini/Huygens	To explore Saturn and its system of rings and moons from orbit	Planetary	An international collaboration between NASA, the ESA, and the Italian Space Agency
January 7, 1998	Lunar Prospector	To create the first complete compositional and gravity maps of the Moon from lunar orbit	Planetary	Successfully demonstrated "faster, better, cheaper" approach[c]
February 26, 1998	Student Nitric Oxide Explorer (SNOE)	To measure the effects of energy from the Sun and magnetosphere on the density of nitric oxide in Earth's upper atmosphere	Solar physics/ space physics	First mission in NASA's Student Explorer Demonstration Initiative (STEDI) program
April 2, 1998	Transition Region and Coronal Explorer (TRACE)	To image the solar corona and transition region at high angular and temporal resolution	Solar physics	The power of TRACE to perform detailed studies of the solar atmosphere made this observatory unique among the current group of spacecraft studying the Sun

Table 4–1. Space Science Launched Missions (1989–1998) (Continued)

Launch Date	Mission	Objectives	Discipline	Remarks
October 24, 1998	Deep Space 1 (DS 1); Students for the Exploration and Development of Space (SEDSAT)	DS 1: To test innovative technologies appropriate for future deep space and interplanetary missions SEDSAT: To contribute to the development and utilization of advanced technology for the general space program	Technology demonstrator	DS 1: First mission under NASA's New Millennium program; SEDSAT: Microsatellite developed and operated by students at the University of Alabama, Huntsville
December 5, 1998[d]	Submillimeter Wave Astronomy Satellite (SWAS)	To better understand star formation by determining the composition of interstellar clouds and establishing the means by which those clouds cooled as they collapsed to form stars and planets	Astrophysics	Provided new information about the physical conditions (density and temperature) and chemistry in star-forming molecular clouds
December 11, 1998	Mars Climate Orbiter	To operate simultaneous investigations of Mars' atmosphere, climate, and surface with Mars Polar Lander	Planetary	Communication with spacecraft lost; unsuccessful mission

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[a] An orbit around Earth-Sun L1 point, which is about four times the distance to the Moon or 1/100 the distance to the Sun–about 1 million miles (1,609,344 km) away from Earth.

[b] mCrab = milliCrab, one thousandth of the intensity of the Crab nebula. X-ray astronomers use this unit when comparing observations from different x-ray detectors on different instruments.

[c] Howard McCurdy, *Faster, Better, Cheaper: Low-Cost Innovation in the U.S. Space Program*, (Baltimore, MD: The Johns Hopkins University Press, 2001), p. 5.

[d] Launch took place at 16:57 Pacific Standard Time on December 5, 1998. Some references state this as December 6, reflecting Eastern Standard Time and Universal Time, but fail to indicate the time zone being used.

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Table 4–2. Attached/Retrieved NASA Space Science Missions

Launch Date	Mission	Objectives	Remarks
December 2, 1990	Astro-1	To provide around-the-clock observations and measurements of UV radiation from celestial objects such as hot stars, galactic nuclei, and quasars[a]	Carried on STS-35/*Columbia*
January 13, 1993	DXS	To collect data on stars and the surrounding galactic gases	Hitchhiker experiment on STS-54/ *Endeavour*
April 11, 1993	SPARTAN 201-01	To study the velocity and acceleration of the solar wind and observe aspects of the Sun's corona	Released from STS-56/*Discovery* and retrieved at end of mission
September 13, 1993	ORFEUS-SPAS	To investigate very hot and very cold matter in the universe using the retrievable ASTRO-SPAS spacecraft built by Germany	Released from STS-51/*Discovery* and retrieved at end of mission
December 2, 1993	First Hubble Servicing Mission	To restore the planned scientific capabilities and reliability of the Hubble Space Telescope and validate the on-orbit servicing concept for Hubble Space Telescope	Accomplished through series of EVAs on STS-61/*Endeavour* mission
September 13, 1994	SPARTAN 201-02	To explain how the Sun generates the solar wind	Released from STS-64/*Discovery* and recovered at end of mission
February 7, 1995	SPARTAN 204	To observe galactic dust clouds and study celestial targets in the interstellar medium, the gas and dust that filled the space between the stars, and the material from which new stars and planets were formed using the FUVIS provided by the Naval Research Laboratory; to obtain far UV spectroscopy of diffuse sources, both natural and human-made[b]	Released from STS-63/*Discovery* and recovered at end of mission

Table 4–2. Attached/Retrieved NASA Space Science Missions (Continued)

Launch Date	Mission	Objectives	Remarks
March 2, 1995	Astro-2	To expand on results obtained on Astro-1 mission; to use the three UV telescopes to make simultaneous observations of objects such as stars, galaxies, and quasars	Carried on STS-67/*Endeavour*
September 8, 1995	SPARTAN 201-03	To study the solar corona and galactic clusters using x-ray, far UV, and visible light instruments	Released from STS-69/*Endeavour*'s bay and recovered at end of mission
November 20, 1996	ORFEUS-SPAS	To launch a deployable/retrievable astronomical platform and obtain UV spectra for both astrophysically interesting sources and the intervening interstellar medium	Deployed and retrieved on STS-51/*Discovery* mission; collaborative U.S.-German Shuttle Astro-SPAS mission
February 11, 1997	Second Hubble Space Telescope Servicing Mission	To repair or replace Hubble Space Telescope instruments and parts to improve productivity and increase lifetime of the telescope	Accomplished through a series of EVAs on STS-82/*Discovery* mission
November 19, 1997	SPARTAN 201-04	To study the origins of the solar wind	Unable to be deployed by STS-87/*Discovery*
October 29, 1998	HOST/SPARTAN 201-05	HOST: To test the instruments that would be used for the third Hubble Space Telescope Servicing Mission; SPARTAN: To study the origins of the solar wind	Reflight of SPARTAN 201-05 mission on STS-95/*Discovery*

[a] "Space Shuttle Mission STS-35 Press Kit," p. 5, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_038_STS-035_Press_Kit.pdf* (accessed May 8, 2006).

[b] "SPARTAN," *http://science.hq.nasa.gov/missions/satellite_66.htm* (accessed May 8, 2006).

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Table 4–3. Authorized Budget (FY 1989–FY 1998) (in thousands of dollars[a])

	1989	1990[b]	1991	1992	1993	1994	1995	1996	1997	1998
Physics and Astronomy	761,600	914,500	985,000	1,104,600[c]	1,096,000[d]	1,094,700[e]	1,081,700[f]	1,167,600[g]	—	—
Planetary Exploration	410,300	366,900[h]	337,200[i]	299,300	472,200[j]	622,200[k]	691,300[l]	827,800[m]	—	—
Space Science (Total)	1,171,900	1,281,400	1,322,200	1,403,900	1,568,200	1,716,900	1,773,000	1,995,400	2,107,400[n]	2,079,800[o]
Change	—	9.3%	3.2%	6.2%	11.7%	9.5%	3.3%	12.5%	5.6%	–1.3%
Rate of Inflation[p]	—	5.4%	4.2%	3.0%	3.0%	2.6%	2.8%	2.9%	2.3%	1.6%

[a] The annual appropriations bills typically did not designate amounts specifically for space science activities. Thus, the Agency used the authorization bill (when passed) and committee proceedings as the basis for its annual operating plan.

[b] No authorization bills were passed for FYs 1990, 1991, and 1994. Figures reflect bills introduced but not passed.

[c] Became P.L. 102–195. Included $3 million for carrying out scientific programs that were otherwise eliminated from the Space Station.

[d] Specified $22,000,000 for the Shuttle Test of Relativity Experiment.

[e] Stated that $20,000,000 was "for augmenting the funding for Mission Operations and Data Analysis (MO&DA) activities by that amount."

[f] Stated in August 3, 1994 version of H.R. 4489. No final authorization bill was passed.

[g] Stated that $51,500,000 was for the Gravity Probe B and "that no funds are authorized for the Space Infrared Telescope Facility."

[h] Did not include amount for CRAF/Cassini mission, which was authorized separately.

[i] Did not include $1,600,000,000 for CRAF/Cassini mission, which was "not to exceed $1,600,000,000 for development, launch, and 30 days of operations thereof…." (Introduced H.R. 5649 *National Aeronautics and Space Administration Multiyear Authorization Act of 1990* and S. 916 agreed to by House.)

[j] Specified $10,000,000 for Magellan mission operations.

[k] Stated that $65,000,000 was "for augmenting funding for Mission Operations and Data Analysis activities and to initiate development of a Mars Environmental Survey mission" (H.R. 2200).

[l] Included $128.7 million for the Discovery Program and $4 million for Venus data analysis. Stated in August 3, 1994 version of H.R. 4489. No final authorization bill was passed.

[m] Stated that $30 million was for New Millennium spacecraft, including $5 million for NASA's participation in Clementine 2.

[n] Amount specified in H.R. 3322, passed by House.

[o] Specified $47.6 million for Gravity Probe B; $5 million for participation in Clementine 2; $3.4 million for the Near Earth Object Survey; $528.4 million for MO&DA, of which $150 million was to be for data analysis; and $5 million for the Solar B program. (H.R. 1275).

[p] Rate of inflation calculated from Bureau of Labor Statistics Inflation Calculator, *http://www.bls.gov/*.

Table 4–4. Programmed Budget (FY 1989–1998) (in thousands of dollars)

	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**[a]	**1996**	**1997**	**1998**
Physics and Astronomy	737,400	859,434	969,167	1,036,677	1,034,861	1,149,000	—	—	—	—
Planetary Exploration	416,600	390,848	473,700	534,221	475,598	771,900	—	—	—	—
Space Science (Total Programmed)	1,155,989	1,252,272	1,444,858	1,572,890	1,512,452	1,922,894	2,032,600[b]	2,175,900[c]	1,969,300[d]	2,043,800
Change	—	8.3%	15.4%	8.9%	–3.8%	27.1%	5.8%	7.1%	–9.4%	3.8%

[a] Beginning with FY 1995 programmed amounts, NASA no longer split the Space Science budget categories into Physics and Astronomy and Planetary Exploration. Although it is possible to individually look at figures for specific space science missions, the budgets for items such as Mission Operations and Data Analysis and Research and Analysis do not indicate whether funds are going toward Physics and Astronomy or Planetary Exploration projects.

[b] Included $255,600,000 million for Launch Services.

[c] Included $245,300,000 million for Launch Services.

[d] Included $240,600,000 million for Launch Services.

Table 4–5. Physics and Astronomy Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Authorization[a]	Programmed
1989	791,600/734,100	761,600	737,400
1990	894,500/861,378	914,500[b]	859,434
1991	985,000/975,100	—	969,167
1992	1,140,600/1,047,300	1,104,600[c]	1,036,677
1993	1,113,500/1,103,860	—	1,034,861
1994	1,074,700/1,067,600	—	1,149,000
1995	1,058,700/1,195,500	—	—
1996	1,131,100/[d]	—	—

[a] If no authorized amount is stated, Congress did not designate an authorized amount for Physics and Astronomy.

[b] Amount stated in proceedings. No authorization bill was passed.

[c] Included $3,000,000 million to carry out scientific programs that were otherwise eliminated from the Space Station.

[d] Physics and Astronomy was no longer a separate budget category.

Table 4–6. Hubble Space Telescope Development Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	102,200/104,900	104,900
1990	67,000/81,800	81,800
1998	—	144,900[a]

[a] Hubble Space Telescope development was reinstated to provide new flight hardware, subsystems, and instruments to extend the telescope's operational life and enhance its capabilities. There was no budget submission for the Hubble Space Telescope development funds in FY 1998.

Table 4–7. Gamma Ray Observatory Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	41,900/50,900	50,900
1990	26,700/35,100	41,200
1991	—/22,000	22,000

Table 4–8. Global Geospace Science Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1989	101,400/64,400	64,400	n/a
1990	112,300/67,200	57,600	n/a
1991	98,500/96,600	96,600	n/a
1992	65,300/75,300	75,300	n/a
1993	60,100/72,647	72,647	n/a
1994	—/13,300	27,600	n/a
1995	—/40,000	40,000	612,600[b]
1996	5,400/—	—[c]	30,100[d]
1997	—	—	25,600[e]
1998	—	—	15,800

[a] Part of the U.S. contribution to the ISTP program.

[b] Included costs for FY 1995 and prior for experiment and spacecraft development for Wind and Polar spacecraft, U.S. contributions to the ISTP program as well as a 2.5-year period of MO&DA, launch support, and unique tracking and data acquisition required during the missions. Wind launched in November 1994 and Polar launched in February 1996.

[c] No budget line item in FY 1996 (revised), FY 1997, and FY 1998 budgets.

[d] Included budget authority for MO&DA, launch support, and tracking and data support.

[e] FY 1997 and FY 1998 budget authority included costs associated with MO&DA and tracking and data support.

Table 4–9. Advanced X-Ray Astrophysics Facility Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full-Cost)[a]
1989	27,000/16,000	16,000	n/a
1990	44,000/44,000	44,000	n/a
1991	113,000/101,200	101,200	n/a
1992	211,000/151,000	150,740	n/a
1993	174,000/168,337	168,337	n/a
1994	260,300/241,300	239,300	n/a
1995	234,300/234,300	224,300	1,101,100[b]
1996	237,600/237,600	237,600	510,500
1997	178,600/178,600	184,400	321,400
1998	92,200/95,800	112,200	273,200

[a] Full-cost budget estimates encompassed early development of the mirror technology; the design and development phase; establishment of a mission-unique science center and preflight ground system development, followed by amounts for the first year of a five-year period (through 2002) of mission operations and science data analysis; the purchase of the inertial upper stage and integration activities; the average cost (including recurring costs for improvements and upgrades) of a FY 1998 Space Shuttle flight; mission-unique tracking and data support costs; and construction of the X-Ray Calibration Facility. These budget estimates also included a pro forma distribution of the average costs of a Space Shuttle.

[b] Total of FY 1995 and prior years.

Table 4–10. Payload and Instrument Development Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed
1989	77,100/71,700	70,500
1990	71,400/90,655	93,038
1991	97,200/94,600	92,600
1992	115,900/116,500	118,300
1993	78,200/99,340	74,240
1994	53,400/59,500	59,500
1995	47,900/53,900	66,000
1996	33,100/30,700	25,900
1997	16,900/16,900	16,900
1998	12,300/18,000	18,000

[a] Payload and instrument development included a wide range of instrumentation—from early test, checkout, and design of instruments for long-duration free-flying missions to international flights of opportunity. The exact instruments funded in this category changed from year-to-year as mission status changed.

Table 4–11. Shuttle/Spacelab Payload Mission Management and Integration Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed
1989	61,500/69,700	67,700
1990	86,100/81,248	75,109
1991	89,100/88,800	88,800
1992	88,000/88,000	78,000
1993[b]	101,100/94,018	94,100

[a] This category included funds to manage the mission planning, integration, and execution of all NASA Spacelab and attached Shuttle payloads. Was included with Space Science Physics and Astronomy budget categories until creation of OLMSA in 1993.

[b] Transferred to OLMSA program. See chapter 3.

Table 4–12. Explorer Development Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed	Budget Authority (Full-Cost)
1989	82,100/82,100	82,100	n/a
1990	93,200/91,800	88,352	n/a
1991	100,800/99,800	99,800	n/a
1992	107,900/105,000	109,100	n/a
1993	112,500/115,832	115,832	n/a
1994	123,300/123,300	123,300	n/a
1995	120,400/120,400	120,400	363,800[b]
1996	129,200/132,200	132,200	199,600[c]
1997	135,000/125,000	117,500	186,400
1998	142,700/113,500	169,300	200,500

[a] The program provided frequent, relatively low-cost missions taken as funding availability permitted within an essentially level program funding profile.

[b] Included costs for FY 1995 and prior, specifically for RXTE, ACE, and FUSE. Funding for FY 1995 and future years included the design and development phase, launch services, mission-unique tracking and data acquisition support, and MO&DA.

[c] Budget authority for FY 1996, FY 1997, and FY 1998 included funds for RXTE, ACE, and FUSE, Medium Explorers, Small Explorers, University Explorers, and Planning and Future Developments.

Table 4–13. Physics and Astronomy Mission Operations and Data Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	156,200/143,200	142,400
1990	204,800/202,400	215,723
1991	293,900/313,300	311,900
1992	388,400/380,800	375,200
1993	440,900/415,385	415,402
1994	416,200/420,700	405,200
1995	441,700/432,400	—
1996	428,600/—[a]	—

[a] Separate MO&DA budget category for Physics and Astronomy disestablished; combined with MO&DA for Planetary Exploration.

Table 4–14. Physics and Astronomy Research and Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	89,100/85,800	85,100
1990	112,500/109,500	104,942
1991	122,500/100,800	98,267
1992	103,100/70,500	69,937
1993	81,400/71,558	71,558
1994	72,200/71,100	71,100
1995	67,200/75,400	—
1996	90,400/—[a]	—

[a] Separate Research and Analysis budget category for Physics and Astronomy disestablished. Combined with Research and Analysis for Planetary Exploration.

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Table 4–15. Space Science Supporting Research and Technology[a] Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1995	—[b]	220,400
1996	—/238,900	239,400
1997	259,200/246,000	426,600
1998	311,200/541,700	894,000

[a] Referred to both as Supporting Research and Technology and as Research and Analysis in accompanying narrative. This budget category supported research in space physics; astrophysics; planetary exploration; mission study and technology development; Space Infrared Telescope Facility (SIRTF) Advanced Technology Development (ATD); Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) ATD; Origins ATD; exploration technology development; information systems; and high-performance computing and communications.

[b] Budget category not established at time of budget submission.

Table 4–16. Space Infrared Telescope Facility (SIRTF) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)[a]
1996	—[b]	—	15,000
1997	—[c]	—	24,900
1998	92,200/55,400	70,200	81,400

[a] Budget authority for FY 1996 and FY 1997 included costs for development of the mission. It did not include amounts for definition phase studies carried out before FY 1996. FY 1998 budget authority included MO&DA in preparation for an anticipated launch in FY 2002.

[b] No budget request for this category included at time of budget submission.

[c] No budget request for this category included at time of budget submission.

Table 4–17. Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1997	—/18,200	25,900	26,900[a]
1998	48,200/52,700	64,400	56,900[b]

[a] Included budget authority for mission development. Costs for definition phase studies carried out from April 1996 to April 1997 are not in this figure.

[b] Included budget authority for mission development and launch support in anticipation of a January 2000 launch.

Table 4–18. Stratospheric Observatory for Infrared Astronomy Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1998	—[a]	45,800

[a] Included with Suborbital Program in prior years.

Table 4–19. Suborbital Program Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	45,100/45,400	45,400
1990	53,500/52,700	52,700
1991	55,000/55,000	55,000
1992	61,000/60,200	60,100
1993	65,300/64,843	64,843
1994	69,500/69,500	69,500
1995	67,200/67,200	67,200
1996	106,700/88,000	88,000
1997	69,100/64,100	59,900
1998	84,400/83,300	—[a]

[a] Programmed amount not stated. Included with Supporting Research and Technology and Stratospheric Observatory for Infrared Astronomy budget categories.

Table 4–20. Gravity Probe-B Development/Relativity Mission Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1993	—[a]	27,000	n/a
1994	—/42,400	42,400	n/a
1995	50,000/50,000	50,000	219,800[b]
1996	51,500/51,500	51,500	51,500
1997	59,600/59,600	59,600	66,400[c]
1998	45,600/57,300	70,800	60,300

[a] Budget category not established at time of submission.

[b] Included costs for FY 1995 and prior. Budget authority for FY 1995 and prior and FY 1996 included costs for mission and experiment development. They did not include the amounts for the definition phase studies carried out from FY 1995 through FY 1997, but they did provide the amounts for the Shuttle Test of Relativity Experiment program initiated in FY 1988 and subsequently restructured into a ground test program only.

[c] Costs for FY 1997 and FY 1998 included estimated budget authority for development and launch support in anticipation at the time of a launch in October 2000.

Table 4–21. Information Systems Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]	25,002
1994	26,500/26,500[b]	26,500
1995	26,500/26,100	—[c]
1996	25,900/—	—

[a] Budget category not established at time of submission.

[b] Moved to Space Applications budget category.

[c] No programmed amount shown in funding documents.

Table 4–22. Planetary Exploration Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	404,000/416,600	416,600
1990	396,900/391,686	390,848
1991	485,200/457,100	473,700
1992	627,300/535,600	534,221
1993	487,200/473,615	475,598
1994	557,200/654,300	771,900
1995	707,300/817,100	—[a]
1996	827,800/—[b]	—

[a] No programmed amount stated for Planetary Exploration.

[b] Separate Planetary Exploration budget category disestablished.

Table 4–23. Galileo Development Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	61,300/73,400	73,400
1990	17,400/17,127	17,127

Table 4–24. Ulysses Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	10,300/10,300	10,300
1990	14,500/14,252	14,252
1991	3,300/3,034	2,757

Table 4–25. Magellan Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	33,900/43,100	43,100

Table 4–26. Mars Observer Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	102,200/102,200	102,200
1990[a]	100,500/98,922	98,922
1991	68,900/78,528	88,528
1992	54,400/76,900	85,000[b]
1993	—	—

[a] Became "Mars Observer Development" in 1990 when Mars Balloon Relay Experiment became a separate budget category.

[b] Mars Observer was launched in September 1992.

Table 4–27. Planetary Exploration Mission Operations and Data Analysis Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed
1989[b]	112,700/110,700	110,700
1990	155,400/156,856	155,956
1991	173,500/161,175	170,152
1992[c]	150,500/156,100	160,721
1993	170,300/163,482	163,465
1994	160,700/141,700	130,700
1995	127,700/117,200	544,600[d]
1996	127,800/563,800	563,600
1997	592,400/583,300	596,500
1998	507,400/528,500	138,700

[a] Objectives of the planetary MO&DA program were in-flight operation of planetary spacecraft and acquisition and analysis of data from those missions.

[b] Mission operations for Galileo began in October 1989 for the spacecraft's six-year journey to Jupiter. The Magellan spacecraft was launched in May 1989 and arrived at Venus in August 1990.

[c] Mars Observer mission operations began in October 1992 when the spacecraft was launched.

[d] Included total MO&DA for all Space Science missions, both Physics and Astronomy and Planetary Exploration missions.

Table 4–28. Planetary Exploration Research and Analysis Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1989	83,600/76,900	76,900
1990	79,100/70,610	70,672
1991	89,500/67,866	67,766
1992	93,200/90,700	76,600
1993	106,900/101,680	101,680
1994	126,400/115,100	107,600
1995	115,100/108,400	—[a]
1996	109,100/—	—

[a] Separate Planetary Exploration Research and Analysis funding category discontinued.

Table 4–29. Comet Rendezvous Asteroid Flyby (CRAF)/Cassini Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1990[a]	30,000/29,519	29,519	n/a
1991	148,000/145,000	143,000	n/a
1992	328,000/210,700[b]	210,700	n/a
1993	210,000/204,953	204,953	n/a
1994	266,600/266,600	166,600	n/a
1995	255,000/255,000	255,000	1,335,500[c]
1996	191,500/191,500	191,500	281,500[d]
1997	106,700/89,600	74,600	187,800
1998	9,000/—	—	91,400[e]

[a] Assumed new start status for the CRAF and Cassini missions in FY 1990. The FY 1990 appropriations bill stated that "no funds…may be used to enter into contracts…for the comet rendezvous and asteroid flyby and Cassini missions (CRAF/Cassini) if the estimated total budget authority for development of the two spacecraft, through launch plus 30 days of the Cassini mission, exceeds $1,600,000,000." H.R. 2916, *Departments of Veterans Affairs and Housing and Urban Development, and Independent Agencies Appropriations Act, 1990.*

[b] The FY 1992 revised estimate reflected a $117.3 million reduction as directed by Congress that required a 15–month launch delay for CRAF from February 1996 to May 1997 and a 23–month delay of the Cassini launch from November 1995 to October 1997. In FY 1993, budget restrictions resulted in termination of the CRAF mission. Consequently, FY 1992 funding was used to terminate CRAF development activities and for major rebaselining for Cassini to reflect the new launch date, new launch trajectories, and the transition from a combined mission environment to a single mission scenario.

[c] Included funding for FY 1995 and prior fiscal years, including costs associated with the CRAF mission cancelled in 1993.

[d] FY 1996 and FY 1997 budget figures included funds for spacecraft and instrument development, launch support, and tracking and data support.

[e] FY 1998 budget authority included spacecraft and instrument development, MO&DA, launch support, and tracking and data support in anticipation of an October 1997 launch.

Table 4–30. Mars Balloon Relay Experiment Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1990	—[a]/4,400	4,400
1991	2,000/1,497	1,497
1992	1,200/1,200	1,200

[a] Budget category not included at time of initial budget submission.

Table 4–31. Mars '94 Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1993	—[a]/3,500[b]	3,500
1994	3,500/3,500	4,400
1995[c]	1,400/2,199	1,400

[a] Budget category not included at time of initial budget submission.

[b] The Mars '94 mission (renamed Mars '96) was a Russian mission composed of an orbiter and two soft landers for deployment on the Martian surface. The United States was to provide two soil oxidation instruments, one for flight aboard each of the two landers. No funds were originally requested in the FY 1993 budget. Later in the FY 1993 budget process, funding was reallocated from the Mars Observer mission operations and Voyager-Neptune data analysis.

[c] During FY 1994, final integration and testing of the two U.S. science instruments was nearing completion, and shipment of the flight units to Russia was scheduled for May 1994 for integration with the rest of the science payload. However, Russian technical problems delayed project completion beyond the October 1994 launch opportunity. This required a two-year launch delay to October 1996, necessitating refurbishment of the instruments and replanning their delivery to Russia for final integration with the rest of the science payload. FY 1995 funding provided ongoing support for the U.S. science investigators associated with all aspects of the science payload. The one-year prime mission was to begin upon arrival at Mars in September 1997. FY 1996 funding was provided to establish science data formatting, archival, and dissemination requirements before initiation of the prime mission.

Table 4–32. Discovery Funding History[a] (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1994	—/127,400	127,400	n/a
1995	129,700/129,700	129,700	345,500[b]
1996	103,800/102,200	102,200	137,500[c]
1997	74,800/76,800	76,800	104,700[d]
1998	106,500/76,500	100,000	146,400[e]

[a] The Discovery Program provided frequent access to space for small planetary missions. The Discovery Program included the Mars Pathfinder, NEAR, Lunar Prospector, and Future Missions budget categories. Future missions not launched by the end of 1998 included the Stardust mission, which had been selected in November 1995.

[b] Included full costs for FY 1995 and prior years for NEAR development, launch support, and tracking and data support; also included Mars Pathfinder development, the microrover, launch support, and tracking and data support.

[c] FY 1996 costs were for NEAR development, MO&DA, launch support, and tracking and data support; Mars Pathfinder development, microrover, launch support, and tracking and data support; Lunar Prospector development; Stardust Phase A/B (concept and definition analysis), development, and launch support; and development of future missions.

[d] FY 1997 budget authority was for NEAR mission operations and data analysis and tracking and data support; Mars Pathfinder microrover, MO&DA, launch support, and tracking and data support; Lunar Prospector development and MO&DA; Stardust development and launch support; and development of future missions.

[e] FY 1998 budget authority was for NEAR MO&DA and tracking and data support; Mars Pathfinder MO&DA and tracking and data support; Lunar Prospector MO&DA; Stardust development and launch support; development of future missions; and future missions' ELVs.

Table 4–33. Mars Surveyor Funding History (in thousands of dollars[a])

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1994	—[b]	14,600	n/a
1995	78,400/59,400	59,400	94,800[c]
1996	108,500/111,900	111,900	145,100[d]
1997	90,000/90,000	90,000	142,900[e]
1998	139,700/145,200	187,900	202,500[f]

[a] Included Mars Global Surveyor, Mars Orbiter and Lander, and future Mars missions.

[b] No budget category established at time of budget submission.

[c] Included costs for FY 1995 and prior years for Mars Global Surveyor development, launch support, and tracking and data support.

[d] FY 1996 costs were for Mars Global Surveyor development, launch support, and tracking and data support; 98 Mars Orbiter/Lander development and launch support; and future Mars missions development.

[e] FY 1997 budget authority was for Mars Global Surveyor MO&DA, launch support, and tracking and data support; 98 Mars Orbiter/Lander development and launch support; and future Mars missions development.

[f] FY 1998 budget authority was for Mars Global Surveyor MO&DA and tracking and data support, 98 Mars Orbiter/Lander development and launch support, and future Mars missions development and launch support.

Table 4–34. Space Science New Millennium Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed	Budget Authority (Full Cost)
1995	—[a]/10,500	—	10,500[b]
1996	30,000/30,000	43,500	47,200[c]
1997	21,500/48,600	—	53,700[d]
1998	75,700	—	108,600[e]

[a] No budget category established at time of initial budget submission.

[b] Included costs for FY 1995 and prior years for Advanced Technology Development, predecessor to the New Millennium Program.

[c] FY 1996 costs were for New Millennium Development (including Deep Space 1 and Deep Space 2 development) and launch support.

[d] FY 1997 budget authority was for New Millennium Development (including Deep Space 1 and Deep Space 2 development), Advanced Radioisotope Thermoelectric Generator, and launch support.

[e] FY 1998 budget authority was for New Millennium Development (including Deep Space 1 and Deep Space 2 development), Outer Planet Technology, Advanced Radioisotope Thermoelectric Generator, the Center for Integrated Space Microsystems, and launch support.

Table 4–35. Advanced Space Technology Funding History (in thousands of dollars)

Year (Fiscal)	Submission	Programmed
1996	—[a]	143,300
1997	—/132,000	—[b]
1998	151,200/—[c]	—

[a] Budget category not established at time of budget submission.

[b] No programmed amount stated.

[c] Not included in revised budget submission.

Table 4–36. Explorer Missions (1989–1998)

Date	Explorer No.	Mission
November 18, 1989	66	COBE
June 7, 1992	67	EUVE
July 3, 1992	68	SAMPEX (Small Explorer mission)
December 30, 1995	69	RXTE
August 21, 1996	70	FAST (Small Explorer mission)
August 25, 1997	71	ACE
February 26, 1998	72	SNOE (STEDI mission)
April 2, 1998	73	TRACE (Small Explorer mission)
December 6, 1998	74	SWAS (Small Explorer mission)

Table 4–37. Cosmic Background Explorer Mission Characteristics

Launch Date/Launch Site	November 18, 1989 / Vandenberg Air Force Base
Date of Reentry	Last instrument turned off December 23, 1993
Launch Vehicle	Delta 5920
NASA Role	Design, development, flight operations, development of the analysis software, and production of the final mission data sets
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• Investigate the beginnings of organization of matter into galaxies, voids, and clusters of galaxies following the Big Bang. • Examine departures from perfect uniformity that must have occurred shortly after the Big Bang, appearing as spectral irregularities and anisotropy in the microwave and far infrared cosmic background radiation. • Search for accumulated light from the very first stars and galaxies.
Orbit Characteristics:	
Apogee	900 km (559 mi)
Perigee	900 km (559 mi)
Inclination (deg)	99
Period (min)	103
Weight	2,206 kg (4,864 lb)
Dimensions	18 ft (5.5 m) long, 15 ft (4.6 m) diameter, 27 ft (8.2 m) deployed
Power Source	Solar array/batteries direct energy transfer
Prime Contractor	In-house project
Instruments and Experiments[b]	• DMR PI: George Smoot, University of California, Berkeley Searched for minute differences in the brightness of background radiation between different parts of the sky to determine whether the Big Bang was equally intense in all directions. The DMR mapped the sky at three wavelengths: 3.3 mm (0.13 in), 5.7 mm (0.22 in), and 9.6 mm (0.38 in). It had three separate receiver boxes, one for each wavelength, mounted so that neither the Sun nor Earth shone directly on them. Each box had two separate receivers tuned to the same frequency to improve the sensitivity of the measurements. • FIRAS PI: John Mather, Goddard Space Flight Center Surveyed the sky to determine whether the cosmic background radiation from the Big Bang had the predicted spectrum (intensity at each wavelength).

Table 4–37. Cosmic Background Explorer Mission Characteristics (Continued)

Instruments and Experiments[c]	Both FIRAS and the DMR could distinguish 1,000 separate parts of the sky. FIRAS picked up radiation by using a trumpet-shaped cone antenna in line with the spacecraft spin axis. Four detectors, each a tiny silicon resistance thermometer glued to a piece of blackened diamond a thousandth of an inch (0.0254 mm) thick and 5/16 inch (0.7.9375 mm) in diameter, were used to sense the radiation collected by the cone antenna. • DIRBE PI: Michael Hauser, Goddard Space Flight Center Searched for light from the earliest stars and galaxies, the luminous energy that may have occurred 200 million years after the Big Bang. DIRBE measured the collective glow of emissions of objects. It covered a wavelength range of 1 micrometer to 300 micrometers and used 10 wavelength filters. The experiment's unobscured, off-axis Gregorian telescope enabled DIRBE to distinguish between nearby and distant objects. This telescope had stops, baffles, and super-polished mirrors to minimize response to objects outside the desired field of view (FOV). Four on board internal reference sources allowed regular monitoring of the responsiveness of each detector. To give accurate colors and polarizations, all detectors made simultaneous observations of the same FOV.
Results	COBE provided strong evidence supporting the Big Bang theory. Data from FIRAS and DMR gave the precise spectrum and a detailed map of temperature variations in the microwave background radiation from the Big Bang. Using data from DIRBE, astronomers detected an infrared background glow across the sky produced by dust warmed by all the stars that have existed since the beginning of time. The infrared radiation put a limit on the total amount of energy released by all the stars in the universe. It also revealed that a surprisingly large amount of starlight in the universe cannot be seen directly by current optical telescopes, perhaps because stars are hidden by dust or are too faint or far away to be seen.[d] COBE completed its all-sky survey on June 18, 1990; helium depletion occurred on September 21, 1990.

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[a] "COBE, Cosmic Background Explorer," *http://library01.gsfc.nasa.gov/gdprojs/projinfo/cobe.pdf* (accessed August 4, 2005).

[b] "COBE Observes Primeval Explosion," NASA Facts, Goddard Space Flight Center (NASA History Office Folder 5893).

[c] "COBE Observes Primeval Explosion," NASA Facts, Goddard Space Flight Center (NASA History Office Folder 5893).

[d] "Astronomers Discover an Infrared Background Glow in the Universe," Release STScI-1998-01, January 9, 1998, *http://hubblesite.org/newscenter/newsdesk/archive/releases/1998/01/text* (accessed May 11, 2006).

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Table 4–38. Extreme Ultraviolet Explorer Mission Characteristics

Launch Date/Launch Site	June 7, 1992 / Cape Canaveral Air Force Station
Date of Reentry	January 30, 2002
Launch Vehicle	Delta II
NASA Role	Project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Mission objectives: • Carry out an "all-sky" survey in the EUV band of the electromagnetic spectrum (wavelengths from 70 angstroms to 760 angstroms). • Perform a "deep survey" of a representative portion of the sky (180 degrees by 2 degrees) at a sensitivity higher than that of the all-sky survey. • Produce maps and catalogs of positions and intensities for EUV sources observed in the all-sky and deep surveys. • Carry out, through a guest observer program, spectroscopic observations of a significant number of the brightest EUV sources in the sky. Science objectives: • Map the structure of the local interstellar medium using data from two simultaneous surveys of the sky. • Produce a catalog of EUV sources, including their positions and temperatures, and map their distribution in space. • Analyze the composition, temperature, and dynamics of EUV sources and identify, using the EUVE spectrometer, the physical mechanisms responsible for EUV emission.
Orbit Characteristics:	
Apogee	527 km (327 mi)
Perigee	515 km (320 mi)
Inclination (deg)	28.4
Period (min)	94.8
Weight	3,275 kg (720 lb) (on-orbit dry mass)[a]
Dimensions	4.5 m by 3 m (14.8 ft by 9.8 ft)
Power Source	Solar array, three 50-Ah batteries
Prime Contractor	Science payload: Space Sciences Laboratory, University of California, Berkeley Spacecraft platform: Fairchild Space
Instruments and Experiments	Science PI: Stuart Bowyer, University of California, Berkeley Instrument PI: Roger Malina, University of California, Berkeley Guest Observer Project Scientist: Carol Christian, University of California, Berkeley

Table 4–38. Extreme Ultraviolet Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Three scanning telescopes: — Two identical Wolter-Schwarzschild Type I grazing incidence mirrors, each with an imaging microchannel plate detector (Scanner A and B) FOV ~5 degrees diameter; two passbands 44 angstroms to 220 angstroms and 140 angstroms to 360 angstroms. — One Wolter-Schwarzschild Type II grazing incidence mirror, with an imaging microchannel plate detector FOV ~4 degrees diameter; two passbands 520 angstroms to 750 angstroms and 400 angstroms to 600 angstroms. • One Wolter-Schwarzschild Type II grazing incidence mirror Deep Survey/Spectrometer Telescope that split light with half of the light fed to an imaging Deep Survey microchannel plate detector and half the light fed to three separate spectrometers; each were combinations of a grating and microchannel plate detector. Each spectrometer had its own bandpasses: shortwave (70 angstroms to 190 angstroms), medium wave (140 angstroms to 380 angstroms), and longwave (280 angstroms to 760 angstroms).[b]
Results[c]	Interstellar Medium Highlights: • Measurement of unexpected ionization fraction (~25 percent) of the helium in the local interstellar medium. • Discovery of a new (auto-ionization) He I interstellar absorption feature at 206 angstroms; extraordinarily valuable as an interstellar helium diagnostic. • Discovering that upper limits to the diffuse background place new constraints on hot local bubble models. • Discovery of beta CMa (Canis Najoris) as a dominant hydrogen ionization source in the local interstellar medium. White Dwarf Highlights: • Discovering that the origin of the strong EUV opacity in hot hydrogen-rich white dwarfs was due to high *Z* elements, not He. • Discovery of a new class of massive white dwarfs. Cataclysmic Variable Highlights: • First direct determination of the accretion hotspot spatial structure. • Measurement of abundance anomalies in several systems. • Outburst spectra of dwarf novae were more complicated than current models.

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Table 4–38. Extreme Ultraviolet Explorer Mission Characteristics (Continued)

Results[d]	Cool Star Highlights: • First determination of the n_e in stellar coronae. • Discovery of high density (10^{13} cm^{-3}) coronal plasmas. • First measurement of stellar coronal abundances. • Found three abundance patterns: cosmic, "FIP (first ionization potentials) effect" enhanced, and metal deficient. • The EUVE had the best available data on the large number and variety of coronal flares; further observations were required to derive flare frequency, flare energy distribution, and plasma conditions. Solar System Highlights: • Discovery of EUV emission from Comet B2 Hyakutake. • First measurement of helium in the Martian atmosphere, indicating the outgassing of Mars was a factor of 30 weaker than that of Earth. Extragalactic Highlights: • At least 10 extragalactic sources were observed spectroscopically, including at least seven active galactic nuclei. • The spectrum of the Type 1 Seyfert NGC 5548 appeared to show two emission lines. Two other Seyfert galaxies (RXJ0437.4-4711 and Mrk 478) showed only continuum. • The brightest BL Lac object, PKS 2155-304, observed with the EUVE, showed evidence of absorption by partially ionized material in a relativistic jet. • The EUV flux from Mrk 421 appeared to be co-spatial with the TeV-producing region. • Detection of >20 extragalactic EUV sources. • Detection of a new 10^6 K gas component in clusters of galaxies. Other Highlights: • Detection of thermal EUV emission from neutron star surfaces. • Anomalous EUV emission from B-stars (factor of ~20 > models).

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[a] "EUVE," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc+1992-031A* (accessed August 5, 2005).

[b] "The EUVE Observatory," *http://heasarc.gsfc.nasa.gov/docs/euve/euve.html* (accessed August 5, 2005).

[c] "Top '10' EUVE Science Highlights," *http://archive.stsci.edu/euve/science/top10_scihl.html* (accessed August 5, 2005).

[d] "Top '10' EUVE Science Highlights," *http://archive.stsci.edu/euve/science/top10_scihl.html* (accessed August 5, 2005).

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics

Launch Date/Launch Site	July 3, 1992 / Vandenberg Air Force Base
Date of Reentry	Operating as of mid-2005
Launch Vehicle	Scout
NASA Role	Spacecraft design, construction, integration, checkout, and operation; project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	• Determine conclusively whether anomalous cosmic rays are singly charged and measure their isotopic composition. • Measure precipitating magnetospheric relativistic electron fluxes, determining their intensity and latitude and local time dependence, for a range of solar activity levels in the declining phase of solar activity. • Measure elemental and isotopic abundances and charge states of energetic solar flare particles in large and small solar events, including events rich in ^{3}He. • Measure galactic cosmic ray elemental abundances up to iron; also measure isotopic abundances for carbon; nitrogen; oxygen; neon; magnesium; silicon; argon; iron; and nickel.
Orbit Characteristics:	
Apogee	675 km (419 mi)
Perigee	550 km (342 mi)
Inclination (deg)	82
Period (min)	97
Weight	Spacecraft: 117 kg (258 lb) Instruments: 40 kg (88 lb)
Dimensions	1.5 m (4.9 ft) high by 0.86 m (2.8 ft) diameter (stowed)
Power Source	Solar arrays, nickel cadmium battery
Prime Contractor	Goddard Space Flight Center

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Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Instruments and Experiments	Mission PI: Dr. Glenn M. Mason, University of Maryland • Heavy Ion Large Area Proportional Counter Telescope (HILT) Co-Investigators: D. Hovestadt, B. Klecker, and M. Scholer, Max Planck Institute, Germany The HILT measured the charge, energy, and mass of cosmic rays in the energy range of about 8.0 MeV-310 MeV/nucleon. Measured galactic cosmic rays and solar energetic particles when it was near Earth's magnetic poles. Determined the energy and elemental composition of anomalous cosmic rays at energies where they were most abundant. Measured the direction, energy, and charge of each nucleus from helium to nickel. The instrument consisted of 1) an array of position-sensitive proportional counters at the entrance, followed by 2) an ionization chamber, 3) another array of position-sensitive proportional counters just before, and 4) a coplanar, 10-element, solid state array of detectors.[a] • Low Energy Ion Composition Analyzer (LEICA) PI: D. Hamilton, University of Maryland The LEICA was a mass spectrometer that identified incident mass and energy by simultaneously measuring the time-of-flight and residual kinetic energy of particles entering the telescope and stopping in one of four silicon solid-state detectors. Measured 0.5 MeV to 5 MeV for solar and magnetospheric ions. The LEICA and HILT were originally designed and constructed as Shuttle flight GASs. • Mass Spectrometer Telescope (MAST) Co-Investigators: E. Stone, California Institute of Technology, and T. von Rosenvinge, Goddard Space Flight Center The MAST determined the direction, energy, element, and isotope of atoms from all elements up to nickel. Isotopes entered the instrument with velocities between about 12 percent and 75 percent of the speed of light. Measured isotropic composition of elements from lithium to nickel in the range of 10 MeV to several hundred MeV.

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Proton/Electron Telescope (PET) Co-Investigators: R. Mewaldt, NASA Jet Propulsion Laboratory; E. Stone, California Institute of Technology; and T. Von Rosenvinge, Goddard Space Flight Center The PET complemented the MAST by measuring the energy spectra and relative composition of protons (18 MeV to 250 MeV) and helium nuclei (18 MeV to 350 MeV/nuclei) coming from Earth's radiation belts, the Sun, interplanetary space, and interstellar space. Also measured the energy spectra of solar flare and precipitating electrons from 0.4 MeV to 30 MeV. Electrons moved at velocities very close to the speed of light and could significantly cause the destruction of ozone high in Earth's atmosphere.
Results[b]	Successfully investigated the composition of local interstellar matter and solar material and the transport of magnetospheric charged particles into Earth's atmosphere. The SAMPEX made discoveries in the following areas: • Anomalous Cosmic Rays — Discovery of the precise location of trapped anomalous cosmic rays in the magnetosphere. — Measurement of the elemental composition of trapped anomalous cosmic rays, including C, N, O, and Ne. — "Early" return of the anomalous cosmic ray component in the 1992 solar minimum period, well before the relativistic ions. — Discovery that trapped anomalous cosmic rays are the dominant component of high-energy (>10 MeV/nuc) ions heavier than helium in the magnetosphere. — Determination that anomalous cosmic rays nitrogen, oxygen, and neon are singly charged. — Determination that the upper limit of anomalous cosmic ray O^{2+} is less than 10 percent of the total anomalous cosmic ray oxygen, thus limiting acceleration timescales in the heliosphere. — Discovery that the interplanetary spectrum of anomalous oxygen extends to at least 100 MeV/nucleon, implying that the anomalous cosmic ray acceleration mechanism (termination shock?) accelerates particles to at least 1.6 GeV.

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Results	— Discovery (in collaboration with Voyager, Ulysses, and Pioneer spacecraft) that the intensity of anomalous cosmic ray oxygen ions increases with heliolatitude during the 1993 approach to solar minimum, in contrast to the opposite behavior observed at the previous solar minimum; this confirms predictions of one class of particle transport theories that include particle drift. — Demonstration (in collaboration with Voyager, Ulysses, and Pioneer spacecraft) that the radial gradients of anomalous cosmic rays are much smaller in the current solar minimum than during the previous solar minimum in 1987. • Solar Energetic Particles — Determination of "normal" solar system isotopic abundances for Ne and Mg in the large solar particle events of October and November 1993. Excesses (factor 4) of neutron-rich isotopes of Ne and Mg in ^{3}He-rich solar particle events. — Demonstration that high-energy (>25 MeV/nucleon) Si and Fe ions in the large solar particle events of late 1992 were in partially ionized charge states, similar to those reported previously for energies near 1 MeV/nucleon. • Magnetospheric Physics — Discovery that magnetospheric electrons are globally accelerated in association with the impact of high-speed solar wind streams. — Evidence for deep dielectric charging as a likely cause of the January 1994 Anik spacecraft anomalies. — Discovery that remnants of relativistic electron belt generated by the March 24, 1991 interplanetary shock persisted until 1993. — Discovery of a radiation belt at L=1.2 composed of roughly equal amounts of ^{3}He and ^{4}He. — Discovery of high-energy (>50 MeV/nucleon) deuterium trapped in the magnetosphere. — Discovery that relativistic electron precipitation routinely has temporal structure at the bounce period.

Table 4–39. Solar Anomalous and Magnetospheric Particle Explorer Mission Characteristics (Continued)

Results	• Middle Atmosphere — Discovery that electron flux variations at SAMPEX altitudes are well correlated with solar wind variations, providing a solar-magnetosphere-middle atmosphere coupling. — Demonstration that the primary relativistic electron flux inputs into the middle atmosphere occur in the range 3.5<L. — Discovery that relativistic electron energy inputs into the middle atmosphere are asymmetric between the Northern and Southern Hemispheres, with the largest inputs occurring in the Southern Hemisphere. Within each hemisphere, there are preferred longitudes for the energy inputs. — Indication that relativistic precipitating electrons provide a significant source of odd nitrogen to the middle atmosphere and can impact middle atmospheric ozone. • Galactic Cosmic Rays — Improved demonstration that the isotopic composition galactic cosmic rays and anomalous component differ significantly.

[a] "Heavy Ion Large Telescope (HILT)," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1992-038A&ex=2* (accessed April 26, 2006).

[b] "SAMPEX—Solar Anomalous and Magnetospheric Particle Explorer," *http://sunland.gsfc.nasa.gov/smex/sampex/mission/* (accessed May 11, 2006).

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Table 4–40. Rossi X-Ray Timing Explorer Mission Characteristics

Launch Date/Launch Site	December 30, 1995 / Cape Canaveral Air Station
Date of Reentry	Still operating as of mid-2005
Launch Vehicle	Delta II
NASA Role	Mission management; provided spacecraft and PCA
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	To investigate the following:[a] • Periodic, transient, and burst phenomena in the x-ray emission from a wide variety of objects. • The characteristics of x-ray binaries, including the masses of the stars, their orbital properties, and the exchange of matter between them. • The inner structure of neutron stars and the properties of their magnetic fields. • The behavior of matter just before it falls into a black hole. • The effects of general relativity that can be seen only near a black hole. • The properties and effects of supermassive black holes in the centers of active galaxies. • The mechanisms causing the emission of x-rays in all these objects. By doing the following:[b] • Using the PCA to make detailed spectrophotometric observations of the brightest 800 x-ray sources in the sky over the 2-keV to 60-keV energy band with a temporal resolution of 1 microsecond energy resolution of <20 percent (6 keV), to a limiting sensitivity of 0.1 milliCrab. • Using the HEXTE to make detailed spectrophotometric observations of the brightest 400 x-ray sources in the sky over the 20-keV to 200-keV energy band with a temporal resolution of 10 microseconds, energy resolution of <20 percent (at 60 keV), to a limiting sensitivity of 0.5 milliCrab at 100 keV. • Using the ASM to monitor more than 75 percent of the sky every orbit over the 2-keV to 10-keV energy band to a limiting sensitivity of 20 milliCrab and a positional determination accuracy of 3 arc minutes by 5 arc minutes for bright sources. • Detecting and performing detailed studies with the PCA and HEXTE instruments within 8 hours of onset of five bright (flux>1 Crab) x-ray novae.
Orbit Characteristics:	
Apogee	580 km (360 mi)
Perigee	580 km (360 mi)
Inclination (deg)	23

Table 4–40. Rossi X-Ray Timing Explorer Mission Characteristics (Continued)

Period (min)	100
Weight	33,200 kg (7.055 lb)
Dimensions[c]	5.4 m by 1.8 m by 1.8 m (18 ft by 6 ft by 6 ft)
Shape	Rectangular
Power Source	Solar panels
Prime Contractor	In-house project
Instruments and Experiments	• PCA PI: Jean Swank, Goddard Space Flight Center The PCA consisted of five large xenon gas detectors with a combined collecting area of two-thirds of a square meter to measure x-rays in the 2 keV to 60 keV region. The PCA collecting area was 6.250 cm^2. The PCA operated in tandem with the HEXTE, and its pointing area overlapped with the HEXTE pointing area, increasing the collecting area by an additional 1,600 cm^2. • HEXTE PI: Richard Rothschild, University of California, San Diego The HEXTE consisted of two clusters of four detectors each that covered the energy range from 20 keV to 200 keV. The HEXTE featured a large area and low background with a 1-degree FOV coaligned with the PCA FOV. The HEXTE operated in tandem with the PCA, and the two together operated as a high-resolution, sensitive x-ray detector.[d] • ASM PI: Alan Levine, Massachusetts Institute of Technology The rotating ASM consisted of three scanning shadow cameras that scanned 70 percent of the sky every 100 minutes at 2 keV to 10 keV and monitored the intensity and long-term behavior of the brightest x-ray sources. The ASM also provided an alert if a source changed state or brightened suddenly, allowing the spacecraft to be maneuvered within a few hours so the PCA and HEXTE could study the event. • Experiment Data System (EDS) PI: Alan Levine, Massachusetts Institute of Technology The EDS consisted of eight Event Analyzers (EAs), of which six were dedicated to the PCA and two to the ASM. Each EA contained an Intel 80286 processor and associated memory. The EAs could be programmed independently in a variety of modes to process incoming events from the instruments.

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Table 4–40. Rossi X-Ray Timing Explorer Mission Characteristics (Continued)

Results	Performed a wide variety of x-ray observations to include: pulsars, neutron stars, black holes, and gamma-ray bursts. Among the mission's discoveries were: • Observed the reappearance of bursting pulsars. • Discovered neutron stars emitting streams of x-rays that pulsed more than 1,000 times a second. The pulses were not strictly periodic but varied slightly from cycle to cycle. Astronomers call them "quasi-periodic oscillations" or QPOs. • Data from the RXTE ASM confirmed the detection of a 77.7-day period from the low mass x-ray binary Cygnus X-2. • Astronomers used the RXTE to observe a black hole that appeared to drag space and time around itself as it rotated. This effect was called "frame dragging" and was predicted by Einstein's Theory of Relativity. This was the first time physical evidence supporting this aspect of Einstein's 1918 theory had been available. • Helped confirm the existence of magnetars as a class of neutron star. • Discovered that a star emitting rapid pulses of x- rays may be the long-sought "missing link" between old neutron stars that emit powerful flashes of x-rays, and older, rapidly spinning neutron stars that emit mainly radio waves. This star, designated SAX J1808.4-3658, was located 12,000 light years away toward the constellation Sagittarius. • The RXTE's PCA was flooded with an intense wave of gamma rays emanating from a magnetar 20,000 light years away, even though the PCA was not pointing at the source. The wave was so powerful that it blasted sensitive detectors on seven scientific spacecraft that were in Earth orbit, or elsewhere in the solar system, to maximum or off-scale levels.
Remarks	The RXTE was the first mission to provide 100 percent of the observing time to the broad scientific community.

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[a] "About RXTE," *http://heasarc.gsfc.nasa.gov/docs/xte/learning_center/what_is_RXTE.html* (accessed October 20, 2005).

[b] Wesley T, Huntress, Jr., to multiple addresses, "XTE Mission Objectives," September 1, 1995 (NASA History Office Folder 11616).

[c] "The Rossi X-ray Timing Explorer," NASA Facts, *http://www.gsfc.nasa.gov/gsfc/spacesci/pictures/2003/0702pulsarspeed/Rossi_Fact_Sheet.pdf* (accessed October 20, 2005).

[d] "Taking the Pulse of the Universe," RXTE Brochure, *http://xte.mit.edu/xte_pulse.html* (accessed October 20, 2005). Also "About RXTE," *http://heasarc.gsfc.nasa.gov/docs/xte/learning_center/what_is_RXTE.html* (accessed August 9, 2005).

Table 4–41. Fast Auroral Snapshot Explorer Mission Characteristics

Launch Date/Launch Site	August 21, 1996 / Vandenberg Air Force Base
Date of Reentry	Operating as of mid-2005
Launch Vehicle	Pegasus XL
NASA Role	Supplied spacecraft; project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To study the microphysics of space plasma and the accelerated particles that cause the aurora. • To measure particles and fields with high temporal and spatial resolution in regions where electrons are energized to form the aurora and ions are accelerated out of the ionosphere into the magnetosphere.
Orbit Characteristics:	
Apogee	4,175 km (2,594 mi)
Perigee	351 km (218 mi)
Inclination (deg)	83
Period (min)	133
Weight	Total observatory: 191 kg (421 lb) Instruments: 51 kg (112 lb)
Dimensions	1.2 m (3.9 ft) diameter by 1.8 m (5.9 ft)
Shape	Octagonal cylinder
Power Source	Solar arrays and battery
Prime Contractor	Goddard Space Flight Center
Instruments and Experiments	• Electric Field Experiment: PI: Charles Carlson, University of California, Berkeley Composed of three orthogonal boom pairs. Spherical sensors deployed on radial wire and axial booms provided information on the plasma density and electron temperature. • Magnetic Field Experiment: PI: Charles W. Carlson, University of California, Berkeley Consisted of two magnetometers mounted 180 degrees apart on deployable graphite epoxy booms. The search coil magnetometer used a three-axis sensor system to provide magnetic field data over the frequency range of 10 Hz to 2.5 kHz. The flux gate magnetometer was a three-axis system using high, stable, low-noise, ring core sensors to provide magnetic field information from dc to 100 Hz.

Table 4–41. Fast Auroral Snapshot Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Time-of-Flight Energy Angle Mass Spectrograph (TEAMS) PI: Charles W. Carlson, University of California, Berkeley The TEAMS was a high-sensitivity, mass-resolving spectrometer measuring full three-dimension distribution functions of the major ion species with one spin of the spacecraft. The experiment covered the core of all plasma distributions of importance in the auroral region. • Electrostatic Analyzers PI: Charles W. Carlson, University of California, Berkeley Sixteen Electrostatic Analyzers configured in four stacks were used for both electron and ion measurements. The four stacks were placed around the spacecraft so that the entire package was provided a full 360 degree FOV. The analyzers provided a 64-step energy sweep, covering approximately 3 keV to 30 keV up to 16 times per second.
Results	This highly successful spacecraft helped scientists answer fundamental questions about the causes and makeup of the aurora.

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[a] "Fast Auroral Snapshot Explorer (FAST)," Institute of Geophysics and Planetary Physics, UCLA, *http://www-ssc.igpp.ucla.edu/fast/* (accessed August 18, 2005).

Table 4–42. Advanced Composition Explorer Mission Characteristics

Launch Date/Launch Site	August 25, 1997 / Cape Canaveral Air Station
Date of Reentry	Operating as of mid-2005
Launch Vehicle	Delta II
NASA Role	Project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	To determine and compare the isotopic and elemental composition of several distinct samples of matter, including the solar corona, interplanetary medium, local interstellar medium, and galactic matter.
Orbit Characteristics	Orbits at Earth-Sun libration L1 point about 1.5 million km (1 million mi) from Earth
Weight	785 kg (1730.6 lb) (includes 195 kg (430 lb) of fuel at launch)
Dimensions	1.6 m (5.2 ft) by 1.0 m (3.3 ft)
Shape	Irregular octagon
Power Source	Four fixed solar arrays
Prime Contractor	The Johns Hopkins University Applied Physics Laboratory, California Institute of Technology Space Radiation Laboratory
Scientific Co-Investigators[a]	PI: Edward Stone, California Institute of Technology/ Jet Propulsion Laboratory Project Scientist: Tycho von Rosenvinge, Goddard Space Flight Center[b] Co-Investigators: Walter Binns, Washington University in St. Louis Peter Bochsler, University of Bern, Switzerland Leonard Burlaga, NASA Goddard Space Flight Center Alan Cummings, California Institute of Technology William Feldman, Los Alamos National Laboratory Thomas Gerrard, California Institute of Technology[c] Johannes Geiss, University of Bern, Switzerland George Gloeckler, University of Maryland Robert Gold, The Johns Hopkins University Applied Physics Laboratory Dieter Hovestadt, Max Planck Institute for Extraterrestrial Physics, Germany Berndt Klecker, Max Planck Institute for Extraterrestrial Physics, Germany Stamatios Krimigis, The Johns Hopkins University Applied Physics Laboratory Glenn Mason, University of Maryland David McComas, Los Alamos National Laboratory

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Table 4–42. Advanced Composition Explorer Mission Characteristics (Continued)

Scientific Co-Investigators[d]	Richard Mewaldt, California Institute of Technology Eberhard Möbius, University of New Hampshire Norman Ness, University of Delaware John Simpson, University of Chicago[e] Mark Wiedenbeck, Jet Propulsion Laboratory
Instruments and Experiments	• Cosmic Ray Isotope Spectrometer (CRIS): Measured the abundances of galactic cosmic ray isotopes with energies from ~100 MeV/nucleon to ~600 MeV/nucleon in the element range from helium to zinc with a collecting power more than 50 times greater than similar previous instruments. Determined the nuclear charge, mass, and kinetic energy of incident cosmic rays that stop in one of four identical stacks of large-area silicon solid-state detectors. • Solar Isotope Spectrometer (SIS): Provided high-resolution measurements of the isotopic composition of energetic nuclei from helium to nickel (Z=2 to 28) in the energy range from ~10 MeV/nucleon to ~100 MeV/nucleon. • Ultra Low Energy Isotope Spectrometer (ULEIS): Measured ion fluxes in the charge range from helium through nickel from about 20 keV/nucleon to 10 MeV/nucleon, covering both suprathermal and energetic particle energy ranges. Performed exploratory measurements of ultra-heavy species (mass range above nickel) in a more limited energy range near 0.5 MeV/nucleon. Studied the elemental and isotopic composition of solar energetic particles and the mechanisms by which these particles were energized in the solar corona. Investigated mechanisms by which supersonic interplanetary shock waves energized ions. • Solar Energetic Particle Ionic Charge Analyzer (SEPICA): Detected the ionic charge state, kinetic energy, and nuclear charge of ions coming from the Sun to determine not only the type of ions present but also the history of those ions within the Sun. • Solar Wind Ion Mass Spectrometer (SWIMS): Provided solar wind composition data for all solar wind conditions. Determined the quantities of most of the elements and a wide range of isotopes in the solar wind. • Solar Wind Ionic Composition Spectrometer (SWICS): Determined the charge of ions and the temperature and speeds of all the major solar wind ions. Covered solar wind speeds from 145 km/s (90 mi/s) (protons) to 1,532 km/s (952 mi/s) (iron).

Table 4–42. Advanced Composition Explorer Mission Characteristics (Continued)

Instruments and Experiments	• Magnetometer (MAG): Consisted of one electronics box mounted on the spacecraft top deck and two sensors mounted at the end of two booms. Measured the local interplanetary magnetic field direction and magnitude. Established the large-scale structure and fluctuation characteristics of the interplanetary magnetic field at 1 AU upstream of Earth as a function of time throughout the mission. • Real Time Solar Wind (RTSW) Data Experiment: The EPAM, MAG, SIS, and SWEPAM instruments on the ACE supplied data to NOAA's Space Environment Center (SEC) for RTSW processing. This data offered up to 1 hour's advance warning of unusual solar activity, such as solar flares and coronal mass ejections, which could cause geomagnetic storms. • Spacecraft Loads and Acoustic Measurements (SLAM): This engineering instrument directly measured the launch vibration environment on the spacecraft during the first 5 minutes of launch. The system consisted of nine low-frequency accelerometer channels covering a frequency range from dc to 100 Hz, six high-frequency accelerometer channels, and three microphone channels, each covering a frequency range from 5 Hz to 2,000 Hz.
Results[f]	As of July 2005, the ACE has been at the L1 point for eight years. Only the SEPICA has failed. The ACE provided new determinations of the composition of the Sun, which comprises more than 99 percent of the matter in the solar system. By measuring how many electrons remained attached to solar wind and higher-energy ions, the ACE measured the (several million degree) temperatures of regions from which these particles originate. Elemental and isotopic composition measurements reveal the composition of the solar atmosphere, as well as composition patterns that arise when some particles are accelerated more easily than others. The broad range of composition measurements that ACE provided made it possible to identify the origin of energetic particle populations observed in interplanetary space and understand the processes by which they are accelerated. Comparisons of the composition of solar wind and higher energy solar particles with that of meteorites, comets, the Moon, planetary atmospheres, and galactic material provided key information on the history of our solar system.

Table 4–42. Advanced Composition Explorer Mission Characteristics (Continued)

Results[g]	ACE's measurements of radioactive isotopes in the galactic cosmic rays have shown that cosmic rays must have been accelerated at least 100,000 years after they were synthesized in supernova explosions. Other isotope measurements show that cosmic rays typically spend about 15 million years in our galaxy before leaving, implying that they must be replenished continually. The relative abundances of the stable isotopes of magnesium, silicon, calcium, iron, and nickel in cosmic rays are found to be very similar to those in solar system material, indicating that the effects of galactic evolution since the creation of the solar system are not large. ACE's studies of solar wind, solar particles, and cosmic rays, in combination with other spacecraft such as Ulysses and Voyager, have provided new insight into the solar wind that envelops our solar system and the nature of its interactions with the galaxy. From its position at L1, the ACE directly measured Earth's ever-changing solar wind and solar particle environment, including interplanetary disturbances that disrupt Earth's magnetic field and cause the aurora. The combination of ACE data from L1 and magnetospheric data from the Polar, Geotail, SAMPEX, and IMAGE spacecraft made it possible to determine how the magnetosphere and upper atmosphere respond to solar variations.
Remarks	On January 21, 1998, NOAA and the ACE project opened the ACE Real Time Solar Wind monitoring capability to the public.

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[a] As of February 2000. "Advanced Composition Explorer," 2nd ed., March 2002, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005). Also "Advanced Composition Explorer (ACE) Project Responsibilities and Key Personnel," *http://www.srl.caltech.edu/ACE/ace_personnel.html* (accessed May 4, 2006).

[b] Jonathan Ormes of Goddard Space Flight Center was the original ACE Project Scientist.

[c] Not included as of February 2000.

[d] As of February 2000. "Advanced Composition Explorer," 2nd ed., March 2002, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005). Also "Advanced Composition Explorer (ACE) Project Responsibilities and Key Personnel," *http://www.srl.caltech.edu/ACE/ace_personnel.html* (accessed May 4, 2006).

[e] Deceased as of February 2000.

[f] "Advanced Composition Explorer," 2nd ed., March 2002, p. 4, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005).

[g] "Advanced Composition Explorer," 2nd ed., March 2002, p. 4, *http://www.srl.caltech.edu/ACE/ASC/DATA/ACEbrochure/ACEbrochure-2nd-ed8.pdf* (accessed August 11, 2005).

Table 4–43. Student Nitric Oxide Explorer Mission Characteristics

Launch Date/Launch Site	February 26, 1998 / Vandenberg Air Force Base
Date of Reentry	December 13, 2003
Launch Vehicle	Pegasus XL
NASA Role	Funding, launch service management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Scientific objectives: • To determine how variations in the solar soft x-radiation produce changes in the density of nitric oxide in the lower thermosphere. • To determine how auroral activity produces increased nitric oxide in the polar regions.
Orbit Characteristics:	
Apogee	580 km (360 mi)
Perigee	535 km (332 mi)
Inclination (deg)	97.75
Period (min)	95.8
Weight	254 lb (115 kg)
Dimensions	36 in (0.9 m) high, 39 in (1 m) wide
Shape	Hexagonal
Power Source	Solar panels, nickel cadmium battery packs
Prime Contractor	University of Colorado at Boulder, LASP
Instruments and Experiments[a]	Mission PI: Charles Barth, University of Colorado • Ultraviolet Spectrometer (UVS): Measured the density of nitric oxide between the altitudes of 100 km (62 mi) and 200 km (124 mi) in the terrestrial upper atmosphere by observing the (1,0) and (0,1) gamma bands. The spectrometer had a focal length of 125 mm (4.9 in). • Auroral Photometer (AP): Determined energy deposited in the upper atmosphere by energetic auroral electrons. It had two channels; both had a circular FOV of 11 degrees full-cone. The AP and UVS photomultiplier electronics were identical, resulting in significant economies in fabrication and operation. • Solar X-ray Photometer (SXP): Measured the solar irradiance at wavelengths from 0.1 nm to 35 nm in the soft x-ray to hard extreme UV portion of the solar spectrum. Each photometer channel consisted of a silicon photodiode. Five photodiodes were flown. Coatings were selected so overlapping bandpasses could isolate key parts of the solar spectrum at low resolution.

Table 4–43. Student Nitric Oxide Explorer Mission Characteristics (Continued)

Instruments and Experiments	The FOV was 70 degrees full cone. The SXP took 12 measurements per spin, centered on the zenith, with a 63-second integration time. Thus, it obtained an integrated solar measurement once per orbit, when the Sun was near the zenith. Data was stored in a buffer, which was emptied once per spin by the spacecraft microprocessor in the same manner as the UVS and AP.
Results	The SNOE remained fully functional until December 12, 2003. It reentered the atmosphere on December 13 after five years, 290 days on orbit. The SNOE determined the influence of the Sun on Earth's upper atmosphere by measuring the amount of nitric oxide in the atmosphere. SNOE observations confirmed previously held suspicions that the solar soft x-ray irradiance was stronger than prior sparsely available data and empirical models suggested. The SNOE demonstrated that solar soft x-ray irradiance and auroral energy deposition controlled the abundance of nitric oxide over the globe; it also provided the results that wintertime midlatitude nitric oxide was controlled by auroral energy while summertime polar nitric oxide was controlled by solar irradiance. The morphology of nitric oxide also provided clues to the processes in the magnetospheric, which led to the auroral energy deposition. Further, the mission's serendipitous observations of polar mesospheric clouds provided an excellent database for climatological studies of these clouds, showing a strong hemispheric asymmetry in their distribution and the strong influence of local dynamics.[b]

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[a] "Scientific Instruments," *http://lasp.colorado.edu/snoe/lib/instruments.html* (accessed August 31, 2005).

[b] Scott Bailey and Charles Barth, letter written by SNOE investigators upon the occasion of SNOE's end of life. *http://snoe.gi.alaska.edu/bailey/SNOE_reentry.htm* (accessed August 31, 2005).

Table 4–44. Transition Region and Coronal Explorer Mission Characteristics

Launch Date/Launch Site	April 1, 1998 / Vandenberg Air Force Base
Date of Reentry	Operational as of mid-2005
Launch Vehicle	Pegasus XL
NASA Role	Project management, developed and built spacecraft
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To follow the evolution of magnetic field structures from the solar interior to the corona. • To investigate the mechanisms of the heating of the outer solar atmosphere. • To investigate the triggers and onset of solar flares and mass ejections. • To explore the three-dimensional magnetic structures that emerge through the visible surface of the Sun—the photosphere—and define both the geometry and dynamics of the upper solar atmosphere: the transition region and corona.
Orbit Characteristics:	
Apogee	600 km (373 mi)
Perigee	650 km (404 mi)
Inclination (deg)	97.8
Period (min)	95
Weight	250 kg (551 lb)
Dimensions	6 ft by 3.5 ft (1.9 m by 1.1 m)
Power Source	Solar cells and battery
Prime Contractor	Spacecraft: Goddard Space Flight Center Telescope: Lockheed Martin
Mission PI	Alan Title, Lockheed Palo Alto and team including 13 other scientists from the United States, Sweden, the United Kingdom, and the Netherlands.
Instruments and Experiments	The single TRACE telescope was of Cassegrain design, 1.6 m (5.2 ft) long with an aperture of 30 cm (11.8 in). The focal length was 8.66 m (28.4 ft). The telescope's FOV was 8.5 by 8.5 arc minutes with a spatial resolution of 1 arc second. The light was focused on a 1024-element by 1024-element CCD detector (0.5 arc second/pixel). The instrument's temporal resolution was less than 1 second, although the nominal temporal resolution was 5 seconds. Exposure times for observations ranged between 2 milliseconds and 260 seconds.

Table 4–44. Transition Region and Coronal Explorer Mission Characteristics (Continued)

Instruments and Experiments	The primary and secondary mirrors had normal-incidence coatings specially designed for EUV and UV observations that divided the mirrors into quadrants. These segmented coatings were designed to provide identically sized, perfectly coaligned images. Which mirror quadrant was used for an observation was determined by the position of a quadrant selector shutter mechanism positioned behind the entrance aperture. Three of the mirror coatings provided for observations in specific iron emission bands. The final mirror coating allowed broadband UV observations. Further selection of UV observations could be made through a filter wheel mounted in front of the CCD.[b]
Results	First light for the telescope occurred on April 20, 1998. Observations have been collected nearly 24 hours per day since then with no significant problems in any segment of the spacecraft, instrument, or mission operations. The telescope has operated successfully in conjunction with the SOHO.

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[a] "Transition Region and Coronal Explorer," *http://sunland.gsfc.nasa.gov/smex/trace* (accessed September 2, 2005). Also "Transition Region and Coronal Explorer (TRACE)," ISD–The Information Systems Division 580, *http://isd.gsfc.nasa.gov/MSE/OnOrbit/TRACE.htm* (accessed September 2, 2005).

[b] "TRACE Imaging Telescope," *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-020A&ex=** (accessed September 27, 2005).

Table 4–45. Submillimeter Wave Astronomy Satellite Mission Characteristics

Launch Date/Launch Site	December 5, 1998 / Vandenberg Air Force Base
Date of Reentry	Made observations until July 21, 2004; the spacecraft was reactivated in June 2005 for a three-month period to support the Deep Impact encounter with Comet 9P/Tempel-1
Launch Vehicle	Pegasus XL
NASA Role	Spacecraft; project management
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	By observing spectral lines emanating from dense molecular clouds, the SWAS would: • Determine the composition of interstellar clouds. • Establish how dense molecular clouds cool as they collapse and form planets.
Orbit Characteristics:	
Apogee	600 km (373 mi)
Perigee	600 km (373 mi)
Inclination (deg)	70
Period (min)	97
Weight	Spacecraft: 285 kg (628 lb) Instrument: 102 kg (225 lb)
Dimensions	Spacecraft: 1.63 m by 1.02 m[a] (5.3 ft by 3.3 ft) Telescope: 55 cm by 71 cm[b] (1.8 ft by 2.3 ft)
Shape	Spacecraft: Roughly octagonal Telescope: Elliptical
Power Source	Solar arrays and battery
Prime Contractor	Goddard Space Flight Center, Harvard-Smithsonian Center for Astrophysics
Instruments and Experiments	Submillimeter Wave Telescope: PI: Gary J. Melnick, Harvard-Smithsonian Center for Astrophysics heading teams from the United States and Germany The SWAS had a 55-cm by 71-cm (1.8 ft by 2.3 ft) elliptical off-axis Cassegrain telescope with a beam width of 4 arc minutes at its operating frequencies. The telescope incorporated dual heterodyne radiometers. The outputs of the two SWAS receivers were combined to form a final intermediate frequency, which extended from 1.4 GHz to 2.8 GHz. An acousto-optical spectrometer provided by the University of Cologne recorded the spectra (taken every 2 seconds by the spacecraft) that were dispersed into 1,400 1-MHz channels by the spectrometer.

Table 4–45. Submillimeter Wave Astronomy Satellite Mission Characteristics (Continued)

Instruments and Experiments	The SWAS instrument consisted of seven major subsystems: 1. The signal detection subsystem consisting of two submillimeter heterodyne receivers built by Millitech Corporation 2. An acousto-optical spectrometer provided by the University of Cologne in Germany 3. The telescope assembly 4. The star tracker assembly 5. The instrument control electronics 6. The instrument structure 7. The thermal control subsystem [c]
Results	The SWAS had successful launch and early operations. Early SWAS results included the discovery that large amounts of water seemed to saturate the interstellar medium; by contrast, molecular oxygen could not be found.[d] "Hibernating" since July 21, 2004, the SWAS was reactivated to full science operations mode to support the 2005 Deep Impact mission.

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[a] "Submillimeter Wave Astronomy Satellite (SWAS)," 1995 Flight Project Data Book, Space Science.

[b] "The Submillimeter Wave Astronomy Satellite (SWAS)," *http://cfa-www.harvard.edu/swas/instrument.html* (accessed August 11, 2005).

[c] "The SWAS Instrument," *http://cfa-www.harvard.edu/swas/instrument.html* (accessed August 11, 2005).

[d] "First Results from SWAS Include Some Surprises," Harvard-Smithsonian Center for Astrophysics Press Release, January 8, 1999, *http://cfa-www.harvard.edu/cfa/ep/pressrel/melnick.html* (accessed October 11, 2005).

Table 4–46. Roentgen Satellite Mission Characteristics

Launch Date/Launch Site	June 1, 1990 / Cape Canaveral
Date of Reentry	End of mission: February 12, 1999
Launch Vehicle	Delta II
NASA Role	High Resolution Imager, launch vehicle, launch services; site of U.S. ROSAT Science Data Center
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	• To conduct an all-sky survey with imaging x-ray and EUV telescopes.[a] 1995 Flight Project Data Book:[b] • Study coronal x-ray emission from stars of all spectral types, • Detect and map x-ray emission from galactic supernova remnants. • Evaluate the overall spatial and source count distributions for various x-ray sources. • Perform detailed studies of various populations of active galaxy sources. • Perform morphological studies of the x-ray-emitting clusters of galaxies. • Perform detailed mapping of the local interstellar medium (EUV survey). Mission Operation Report:[c] • Measure the spatial, spectral, and temporal characteristics of discrete cosmic sources including normal stars, collapsed stellar objects, and active galactic nuclei. • Perform spectroscopic mapping of extended x-ray sources including supernova remnants, galaxies, and clusters of galaxies. • Conduct mission operation observations of cosmic sources with unprecedented sensitivity and spatial resolution over the 0.1 keV to 2.0 keV energy band.
Orbit Characteristics:	
Apogee	580 km (360 mi)
Perigee	580 km (360 mi)
Inclination (deg)	53
Period (min)	96
Weight	2,424 kg (20,776 lb)
Dimensions	4.5 m by 3 m (14.8 ft by 9.9 ft)
Power Source	Solar panels and a rechargeable battery
Prime Contractor	Dornier

Table 4–46. Roentgen Satellite Mission Characteristics (Continued)

Instruments and Experiments[d]	• XRT PSPC PI: Joachim Trümper, Max Planck Institute, Germany HRI PI: Martin Zombeck, Smithsonian Astrophysical Observatory, Cambridge, MA Consisted of four nested Wolter-I mirrors; mirror assembly had a 2.40-m (7.9-ft) focal length. The focal plane instrumentation consisted of a carousel on which there were two PSPCs, each with a filter wheel carrying a boron filter and HRI. WFC PI: Kenneth Pounds, University of Leicester, UK Consisted of three nested Wolter-Schwarzschild mirrors (coaligned with the XRT); mirror assembly had a 0.525-m (1.7-ft) focal length. Focal plane instrumentation consisted of a curved microchannel plate (MCP), a carousel with eight filters, of which six were science filters.
Results	ROSAT's highlights included: • Detailed exploration of a million-degree, low-density halo of gas surrounding the Milky Way galaxy. • Detection of large gas halos glowing in x-rays from virtually all comets passing near the Sun, produced by the interaction of the comet's gas and fast-moving subatomic particles in the solar wind. • Detection of clusters of galaxies at a larger distance than expected, leading scientists to question how such massive objects could form so early in the history of the universe. • Detection of an isolated nearby neutron star, which, according to previous theories, had been large enough at one time to collapse into a black hole and therefore led scientists to question how massive a star can get without its lifecycle ending in a black hole stage. • Revolutionary discoveries about star formation, including the observation that a large fraction of young stars lie far away from "classical" star-forming regions, indicating that star formation is a more ubiquitous process than previously thought and x-ray emission from young stars plays a key role in the regulation of the star formation rate. • Measurement of the total amount and distribution of dark matter in assemblages of galaxies, with x-ray-emitting gas tracing the effect of gravity and showing that the distribution of dark matter differs from that of the galaxies as seen in visible light. [e]

Table 4–46. Roentgen Satellite Mission Characteristics (Continued)

Results	The ROSAT successfully completed its six-month all-sky survey phase and primary mission of 20 months, including the pointed observations of selected celestial targets. The ROSAT continued to collect data during its extended mission. The satellite was turned off on February 12, 1999 after failure of the telescope's last working detector.

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[a] Max Planck Institut Für Extraterrestrische Physik, *ROSAT User's Handbook http://agile.gsfc.nasa.gov/docs/rosat/ruh/handbook/handbook.html* (accessed August 9, 2005).

[b] "Roentgen Satellite (ROSAT)," *1995 Flight Project Data Book* (NASA History Office Folder 6328).

[c] Mission Operation Report, "Roentgensatellit (ROSAT)," Report no. E-876-90-03 (NASA History Office Folder 30959).

[d] *ROSAT User's Handbook*, *http://agile.gsfc.nasa.gov/docs/rosat/ruh/handbook/handbook.html* (accessed August 9, 2005).

[e] "ROSAT Wrap-Up: ROSAT X-ray Telescope Mission Comes to an End," ROSAT Guest Observer Facility, *http://agile.gsfc.nasa.gov/docs/rosat/taps.html* (accessed August 9, 2005).

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Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics

Launch Date/Launch Site	July 25, 1990 / Cape Canaveral
Date of Reentry	Contact with the CRRES was lost on October 12, 1991, presumably due to on board battery failure.
Launch Vehicle	Atlas Centaur
NASA Role	Operations relating to spacecraft integrity; tracking and control; launch; on-orbit initialization/checkout of the spacecraft; and chemical release campaigns[a]
Responsible (Lead) Center	Marshall Space Flight Center
Mission Objectives	• Launch of the spacecraft into a highly elliptical GTO with an initial perigee of 350 km (217 mi) altitude and an apogee at geosynchronous altitude of 35,780 km (22,233 mi) and inclined at near 18 degrees to the equator. • NASA performance of active chemical release experiments in the ionosphere and magnetosphere. • DOD studies of microelectronic components as the CRRES travels through the inner and outer radiation belts of Earth. • DOD low-altitude studies of ionospheric irregularities, performed in the ionosphere near the orbit perigee.
Orbit Characteristics:	
Apogee	33,786 km (20,994 mi); initial orbit was 350 km by 33,584 km (217.5 mi by 20,868 mi)
Perigee	350 km (217.5 mi)
Inclination (deg)	18.15
Period (min)	590
Weight	1,724 kg (3,800 lb)
Dimensions	2.6 m (8.5 ft) diameter, 1 m (3.3 ft) high, 3 m (9.8 ft) between opposite faces
Shape	Octagonal prism
Power Source	Solar arrays, batteries
Prime Contractor	Ball Aerospace Systems Group (spacecraft)

Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics (Continued)

Instruments and Experiments	• G-1 through G-4: Diamagnetic Cavity, Unstable Velocity Distributions, Plasma Coupling PIs: Robert Hoffman, Goddard Space Flight Center; Steven Mende, Lockheed Palo Alto Research Labs Magnetic and solar storms inject plasma into the magnetosphere. The reaction of the natural magnetosphere to these injections is important to understanding energy and particle transport. Injections of barium ions simulate natural plasma injections in a precisely controlled manner. These four injections were at different altitudes and magnetic field strengths to understand how different regions of space react to artificial cloud plasmas. • G-5: Stimulated Electron Precipitation to Produce Auroras PI: Gerhard Haerendel, Max Planck Institut; Paul Bernhardt, Naval Research Laboratory Neil Brice proposed in 1970 that injections of artificial ion clouds in the Van Allen radiation belts would cause the high-energy charged particles to "unstick" from the magnetic field and crash into the atmosphere. Injecting artificial lithium plasma in a region of high-energy, trapped electrons, tested this theory. To search for artificial auroras created by these particles, observers with optical instruments and radars closely monitored the magnetic field line footprint where it entered the atmosphere in Canada and South America. • G-6: Stimulation of Ion-Cyclotron Waves and Artificial Ion Precipitation PI: Steven Mende, Lockheed Palo Alto Research Lab High-energy protons dominate the premidnight sector of the high-altitude magnetosphere. Some of these protons "leak out" of stable trapped orbits and precipitate into the atmosphere to cause a weak aurora. This experiment injected an artificial lithium plasma cloud into this proton region and measured any increased proton precipitation. This experiment had the same objectives as the previous electron experiment, except that the particles of interest were protons. The enhanced precipitation was detected by optical instruments at the base of the magnetic field line as these protons produced light in the distinct wavelengths of the hydrogen atom. The CRRES instruments monitored the state of the magnetosphere and helped determine the best time for the release.

Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics (Continued)

Instruments and Experiments	• G-7: Ion Tracing and Acceleration PI: William Peterson, Lockheed Palo Alto Research Lab The release of tracer lithium ions were tracked by instruments aboard NASA's Dynamics Explorer 1, the CRRES, Spacecraft Charging at High Altitudes (SCATHA), and the Japanese Akebono satellites. The previous two lithium releases could be used for this experiment, but this release was made when the relative positions of the satellites were favorable for observing the artificial tracer ions. • G-8: Gravitational Instability, Field Equipotentiality, Ambipolar Acceleration PI: Gernard Haerendel, Max Planck Institut Space plasmas often become highly irregular and structured. Electric and magnetic fields are important to this process, but less is known about the effects of gravity. For the light protons in the magnetosphere, it is safe to assume that the effect of gravity is negligible compared to electric and magnetic forces. For the heavier ions, such as oxygen and nitrogen, this assumption about gravity is questionable. This release created a heavy barium plasma along a magnetic field line, and the distortions due to gravity were studied with optical instruments and the radar at Jicamarca, Peru. • G-9: Velocity Distribution Relaxation and Field Equipotentiality PIs: Morris Pongratz, Los Alamos National Laboratory; Gene Wescott, University of Alaska The CRRES satellite released gas at orbital velocity, and the ion clouds formed moved very rapidly (8 km to 10 km per second [5 miles to 6.2 miles per hour]) relative to the natural ionosphere. This state is common in nature, occurring when beams of electrons enter the auroral zone or when material is pulled into a star. The beams eventually slow down; they do not slow through physical collisions between particles, as is the case with neutral gases. Instead, the long-range electrical and magnetic forces that act on the charged particles dominate the physics of beam-plasma interactions. The exact mechanisms of these interactions are not well understood. In this experiment, barium was released over an extensive network of ground and aircraft observatories in the Caribbean while instruments on the CRRES measured the electric and magnetic fields resulting from the interactions.

Table 4–47. Combined Release and Radiation Effects Satellite Mission Characteristics (Continued)

Instruments and Experiments[b]	• G-10: Stimulating a Magnetospheric Substorm PI: David Simons, Los Alamos National Laboratory Sometimes during a magnetospheric substorm, a very large number of charged particles reach the atmosphere together, causing a very bright aurora. This experiment attempted to create a substorm by injecting an artificial barium plasma at the precise moment that the magnetosphere was unstable, "pushing the magnetosphere over the edge." Since barium ions could be seen glowing in sunlight (the particles normally cannot be seen), scientists could obtain a clear visual picture of magnetic substorm creation and behavior. • G-11, G-12: Mirror Force, Field Equipotentiality, Ambipolar Acceleration PI: Gene Wescott, University of Alaska As the release of barium ions flows along magnetic field lines, it will be affected by electric fields. By tracking the details of the ions' motion, these electric fields can be measured. Such electric fields are important in controlling inter-hemispheric flows of electrons and ions. The releases over the Caribbean filled the entire magnetic field line from the equator the other end in South America. Observations from ground and aircraft observatories in the Caribbean and South America pinpointed ion motion details. • G-13, G-14: Critical Velocity Ionization PI: Gene Wescott, University of Alaska The objective of these releases was to investigate the critical ionization velocity phenomenon, first proposed to explain mass differentiation in planetary formation—why the inner planets are made of heavy material and the outer planets are mostly hydrogen. The critical ionization velocity model states that if the relative velocity of electrically neutral chemical species and magnetized plasma is large enough, ionization of the neutral gas will take place even though the energy available is less than that required for ionization. Barium, calcium, and strontium were released in these experiments. These materials had a range of critical ionization velocities, allowing study of the effect over a wide range of this parameter.
Results	Successful mission until battery failure on October 12, 1991.

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[a] Mission Operation Report, Report no. S-145-90-02, "USAF/NASA Combined Release and Radiation Effects Satellite," (NASA History Office Folder 5700).

[b] "Combined Release and Radiation Effects Satellite (CRRES) Press Kit," (NASA History Office Folder 5700)

Table 4–48. Hubble Space Telescope Mission Characteristics

Launch Date/Launch Site	April 25, 1990 / Kennedy Space Center
Date of Reentry	Operating as of mid-2005.
Launch Vehicle	STS-31/*Discovery*
NASA Role	• Marshall Space Flight Center: Development, assembly, and test; launch and deployment; on-orbit verification of system and science instrument functions. • Goddard Space Flight Center: Overall management of daily on-orbit operations; overall operational and servicing mission preparations; development, integration, and test of replacement hardware, space support equipment, and crew aids and tools. • Johnson Space Center: Astronaut training, Shuttle operations, overall mission management, and crew aids and tools. • Kennedy Space Center: Launch services, overall management of launch and post-orbit operations for mission hardware.
Responsible (Lead) Center	Marshall Space Flight Center; transferred to Goddard Space Flight Center when the Orbital Verification phase was nearing completion (about six months after launch).
Mission Objectives	Original science objectives: • To determine the constitution, physical characteristics, and dynamics of celestial bodies; the nature of processes occurring in stellar objectives; the history and evolution of the universe; and whether the laws of nature are universal in the space-time continuum.[a] SM1 objectives: • To restore planned scientific capabilities. • To restore reliability of vehicle systems. • To validate the on-orbit servicing concept for the Hubble Space Telescope. SM2 objectives: • To improve the telescope's productivity. • To extend the telescope's wavelength range into the near infrared for imaging and spectroscopy. • To greatly increase the efficiency of spectrographic science. • To replace failed or degraded spacecraft components.
Orbit Characteristics:[b]	
Apogee	569 km (307 nmi, 353 mi)
Perigee	569 km (307 nmi, 353 mi)
Inclination (deg)	28.5
Period (min)	97
Weight	24,500 lb (11,110 kg)

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Dimensions	Length: 43.5 ft (13.3 m) Diameter: 14.0 ft (4.3 m) with solar arrays stowed; 40.0 ft (12.0 m) with solar arrays deployed Solar array: 7.9 ft by 39.9 ft (2.4 m by 12.1 m)
Main Mirror Characteristics[c]	Diameter: 94.5 in (2.4 m) Weight: 1,825 lb (821 kg) Coating: 0.075 micron aluminum covered with 0.025 micron magnesium fluoride over 70 percent at hydrogen Lyman-Alpha Reflectivity: 70 percent in the UV wavelengths and greater than 85 percent at visible wavelengths
Shape	Cylindrical
Power Source	Solar arrays and nickel hydrogen batteries
Prime Contractor	Lockheed Martin; Ball Aerospace: science instruments for SM1 and SM2
Instruments and Experiments	Original instruments: • WFPC PI: James A. Westphal, California Institute of Technology The WFPC, built by JPL, was used to obtain high resolution images of astronomical objects across a relatively wide FOV and a broad range of wavelengths (1,150 angstroms to 11,000 angstroms). The WFPC enabled scientists to investigate the age of the universe and search for new planetary systems around young stars. The WFPC compared near and far galaxies and observed comets such as Halley's comet, which previously could be viewed only every 75 years. The WFPC was used in two ways: in wide-field mode, the FOV allowed pictures of hundreds of distant galaxies at once; and in planetary mode, the camera provided close-ups of all the planets in our solar system except Mercury, which is too close to the Sun for safe pointing. The WFPC observed larger areas of the sky and more varied forms of light (from far UV to near infrared) than other science instruments. Although the FOV of the telescope's WFPC was greater than that of other telescope instruments, the "wide field" was less than typical ground-based wide-field cameras, which have a FOV of around 5 degrees. This camera's FOV was only 2.67 arc minutes. The camera would take about 100 "wide-field" images to get a picture of the full Moon. The narrower FOV allowed much better resolution of distant objects.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• FOC PI: F. Duccio Macchetto, ESA/STScI The FOC extended the reach of the Hubble Space Telescope and produced the telescope's sharpest images. The FOC photographed stars five times farther away than ground-based telescopes. Many faint stars and galaxies appeared as blazing sources of light to the FOC. The FOC's primary use was to obtain images in more detail than the WFPC. The FOC had two complete detector systems. Each used an image intensifier tube to produce an image on a phosphor screen 100,000 times brighter than the light received. This phosphor image was then scanned by a sensitive electron-bombarded silicon (EBS) television camera and stored in the camera's memory for transmission to the ground. This system was so sensitive that objects brighter than 21st magnitude had to be dimmed by the camera's filter systems to avoid saturating the detectors. Even with a broadband filter, the brightest object that could be accurately measured was 20th magnitude.[d] The FOC helped determine the distance scale of the universe, peered into the centers of globular star clusters, photographed phenomena so faint they could not be detected from the ground, and studied binary stars (two stars so close together they appeared to be one). It was part of the ESA's contribution to the Hubble Space Telescope program. The FOC offered three focal ratios: f/48, f/96, and f/288 on a standard television picture format. The f/48 image measured 22 arc seconds by 22 arc seconds and yielded a resolution (pixel size) of 0.043 arc second. The f/96 mode provided an image of 11 arc seconds by 11 arc seconds on each side and a resolution of 0.022 arc second. The f/288 FOV was 3.6 arc seconds by 3.6 arc seconds, with resolution down to 0.0072 arc second. The FOC weighed 700 lb (318 kg) and was 3 ft by 3 ft by 7 ft (0.9 m by 0.9 m by 2.2 m) in size. The ESA, Dornier Systems, and Matra-Espace Corporation built the instrument.[e]

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• FOS PI: R.J. Harms, Applied Research Corp. (formerly with University of California, San Diego) The FOS spread out the light gathered by a telescope so it could be analyzed to determine properties of celestial objects. Properties of these celestial objects included their chemical composition and abundances, temperature, radial velocity, rotational velocity, and magnetic fields. The FOC also analyzed the properties of extremely faint objects in both visible and UV light. It studied the chemical properties of comets before they approached close enough to the Sun for their chemistry to be altered, as well as probing to see the composition of quasars. This instrument compared galaxies relatively near Earth with those at great distances, helping researchers determine the history of galaxies and the rate at which the universe was expanding. The FOS examined fainter objects than the GHRS and studied these objects across a much wider spectral range—from the UV (1,150 angstroms) through the visible red and the near-infrared (8,000 angstroms)—than the GHRS. The FOS could isolate individual light sources from those surrounding them at very great distances. Two occulting devices blocked out light from the center of an object while allowing the light from just outside the center to pass through. This allowed analysis of the shells of gas around red giant stars of the faint galaxies around a quasar. This instrument used two 512-element Digicon sensors (light intensifiers). The "blue" tube was sensitive from 1,150 angstroms to 5,500 angstroms (UV to yellow). The "red" tube was sensitive from 1,800 angstroms to 8,000 angstroms (longer UV through red). Light entered the FOS through any of 11 different apertures from 0.1 arc seconds to about 1.0 arc seconds in diameter. The FOS had two modes of operation: at low resolution, it could reach 26th magnitude in 1 hour with a resolving power of 250; and at high resolution, the FOS could reach only 22nd magnitude in 1 hour (before the signal-to-noise ratio became a problem), but the resolving power was increased to 1,300.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• GHRS PI: John C. Brandt, Jr., University of Colorado, Boulder The GHRS was the only science instrument devoted entirely to UV spectroscopy. In contrast to the FOS, the spectrograph's detectors were designed to be insensitive to visible light, since the UV emissions from stars were often hidden by the much brighter visible emissions and traded the extremely faint objects detected by FOS for the ability to analyze very fine spectral detail. The GHRS separated incoming light into spectral components so the composition, temperature, motion, and other chemical and physical properties of the objects could be analyzed. Like the FOS, the GHRS used two 521-channel Digicon electronic light detectors; however, the GHRS detectors were blind to visible light. One tube was sensitive from 1,050 angstroms to 1,700 angstroms, while the other was sensitive from 1,150 angstroms to 3,200 angstroms. The "high resolution" in this instrument's name refers to high spectral resolution, or the ability to study the chemical fingerprints of objects in very great detail. The combination of this spectral resolution with the high spatial resolution of the cameras allows scientists to determine the chemical nature, temperature, and density of the gas between stars. The spectrograph's investigations range from peering into the center of far-away quasars to analyzing the atmospheres of planets in our own solar system. The GHRS had three resolution modes: low, medium, and high. Low resolution was 2,000—higher than the best resolution available on the FOS. Examining a feature at 1,200 angstroms, the GHRS could resolve detail of 0.6 angstroms and examine objects down to 19th magnitude. At medium resolution of 20,000, that same spectral feature at 1,200 angstroms could be seen in detail down to 0.06 angstroms; however, the object must be brighter than 16th magnitude. High resolution was 100,000, allowing a spectral line at 1,200 angstroms to be resolved down to 0.012 angstroms. High resolution could be applied only to objects of 14th magnitude or brighter. The GHRS also could discriminate between variations in light from objects as rapid as 100 milliseconds apart.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• HSP PI: Robert C. Bless, University of Wisconsin, Madison The HSP, a simple but precise light meter, measured the brightness of objects being studied, as well as any variations in that brightness with time, in both visible and UV ranges. The photometer studied the smallest astronomical objects of any of the telescope's instruments. One of the photometer's tasks was to look for clues that black holes existed in binary star systems. Variations in brightness would occur as one star revolved around the other. Irregularities in variation might indicate that matter was being lost to a black hole—an object so dense that nothing, not even light, could escape from it. The photometer also provided astronomers with an accurate map of the magnitude of stars. • Fine Guidance Sensors: PI: William H. Jefferys, University of Texas, Austin The fine guidance sensors, built by Perkin-Elmer Corporation, were one of five different types of sensors used by the Hubble Space Telescope's pointing control system to point the telescope at a target. The three fine guidance sensors served a dual purpose. Two of the sensors locked on to reference stars to point the telescope to a precise position in the sky, and then held at that position with an accuracy of 0.01 arc second. The guidance sensors locked on to a star and then measured any apparent motion to an accuracy of 0.0028 arc second. This gave the Hubble Space Telescope the ability to remain pointed at the target with no more than 0.007 arc second of deviation during long periods of time. This level of stability was comparable to being able to hold a laser beam focused on a dime 200 miles (322 km) away (about the distance from Washington, DC to New York City). This sensor, in addition to serving as a backup unit, was used for astrometry—the science of measuring the angles between astronomical objects and determining precise positions and motions of stars and other celestial objects. These measurements were combined with information from other instruments to prepare a more accurate distance scale of the universe.[f] The fine guidance sensors could provide star positions about 10 times more precisely than those observed from a ground-based telescope. When used for astrometric science, the fine guidance sensors let the Hubble Space Telescope do the following:

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	— Search for the wobble in the motion of nearby stars that could indicate the presence of a planetary companion. — Determine if certain stars were really double stars. — Measure the masses of stars. — Measure the angular diameter of stars, galaxies, etc. — Refine the positions and the absolute magnitude scale for stars. — Help determine the true distance scale for the universe.[g] First Servicing Mission: • WFPC2 PI: John T. Trauger, California Institute of Technology WFPC2, built by JPL, was a spare instrument developed in 1985 by JPL in Pasadena, California. The WFPC2 replaced the original WFPC. WFPC 2 had four CCD cameras arranged to record simultaneous images in four separate FOVs at two magnifications.[h] The relay mirrors in WFPC2 were spherically aberrated to correct for the spherically aberrated primary mirror of the observatory. It observed in a wavelength from 1,200 angstroms to 10,000 angstroms.[i] The "heart" of WFPC2 consisted of an L-shaped trio of wide-field sensors and a smaller, high-resolution ("planetary") camera in the square's remaining corner.[j] The instrument weighed 619 lb (280 kg). The camera was 3.3 ft by 5 ft by 1.7 ft (1 m by 1.3 m by 0.5 m), and the radiator was 2.6 ft by 7 ft (0.8 m by 2.2 m). • COSTAR: The COSTAR, built by Ball Electro-Optics & Cryogenics Division, was not a science instrument; it was a corrective optics package that displaced the HSP during the first servicing mission. The COSTAR was designed to optically correct the effects of the primary mirror's aberration on the FOC. (All other instruments installed on later servicing missions were designed with their own corrective optics. When the FOC was replaced by another instrument, the COSTAR was no longer needed.) The COSTAR weighed 640 lb (290 kg) and was 3 ft by 3 ft by 7 ft (0.9 m by 0.9 m by 2.2 m). Second Servicing Mission: • STIS PI: Bruce E. Woodgate, Goddard Space Flight Center

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	The STIS, built by Ball Aerospace Systems Group, spanned UV, visible, and near infrared wavelengths. It separated the light gathered by the telescope into component colors, allowing scientists to analyze the composition of celestial objects, their temperature and motion, and other chemical and physical properties. The STIS's main advance was the capability for two-dimensional rather than one-dimensional spectroscopy. The STIS's two-dimensional detectors allowed the instrument to gather 30 times more spectral data and 500 times more spatial data than existing spectrographs on the Hubble Space Telescope, which looked at one place at a time. This capability recorded many regions in a planet's atmosphere or many stars within a galaxy in one exposure, making the Hubble Space Telescope faster and more efficient. One of the greatest STIS advantages was in the study of supermassive black holes. The STIS contained a new generation electronic light sensor called a Multi-Anode Microchannel Array (MAMA), as well as a CCD. The STIS's coronograph allowed it to search the environment of bright stars for very faint companion objects (possible planets). The STIS could also take UV images like a camera. The STIS could do the following: — Search for massive black holes by studying the star and gas dynamics around galactic centers. — Measure matter distribution in the universe by studying quasar absorption lines. — Use high sensitivity and ability to detect fine detail to study stars forming in distant galaxies. — Perform spectroscopic mapping—measuring chemical composition, temperature, gas density, and motion across planets, nebulae, and galaxies.The STIS was 2.2 m by 0.89 m by 0.89 m (7.1 ft by 2.9 ft by 2.9 ft) and weighed 318 kg (700 lb). Following installation and calibration, the STScI managed STIS operation.

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Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	• NICMOS PI: Rodger I. Thompson, University of Arizona The NICMOS, built by Ball Aerospace Systems Group and Rockwell International, provided the capability for infrared imaging and spectroscopic observations of astronomical targets. The NICMOS detectors performed better than previous infrared detectors. The NICMOS gave astronomers their first clear view of the universe at near-infrared wavelengths between 0.8 micrometers and 2.5 micrometers—longer wavelengths than the human eye could see. The expansion of the universe shifted the light from very distant objects to longer red and infrared wavelengths. The NICMOS's near-infrared capabilities provided views of objects too distant for research by current Hubble Space Telescope instruments that were sensitive only to optical and UV wavelength light. The NICMOS could do the following: — Probe objects created near the beginning of the universe. — Look deeper into clouds of dust to view how stars and planets were formed. — Detect cold objects, such as brown dwarfs, that emit light most brightly at infrared wavelength. The NICMOS contained three cameras, each with a different spatial resolution. Camera 1 had the highest resolution for very fine detailed pictures at shorter near-infrared wavelengths. Camera 2 had the next highest resolution for detailed pictures at longer wavelengths. Camera 3 had a much wider FOV to encompass extended objects at slightly lower resolution. Each camera had wheels of filters and optical components. The cameras could operate independently while others were taking images. As well as a camera, the NICMOS was a spectrometer, a coronograph, and a polarimeter. Each of these operational modes was initiated by rotating the proper element in a wheel containing filters and optical components into the camera beam. A combination of grating and a prism called a "grism" provided spectroscopy for the NICMOS. Polarizers in the wheel were rotated into place when observers wanted to determine the degree of polarization of radiation from a celestial object. One of the cameras had a special set of masks, called a coronograph, to block light from a bright object to observe an adjacent faint object, such as a faint planet near a bright star. The sensitive infrared detectors in the NICMOS must operate at very cold temperatures, 58 K (minus 355°F), because any surrounding heat would create extra infrared signals that interfered with the actual signal from the object being studied.

Table 4–48. Hubble Space Telescope Mission Characteristics (Continued)

Instruments and Experiments	The NICMOS kept its detectors cold inside a cryogenic dewar (a thermally insulated container) containing frozen nitrogen. The dewar cooled the detectors for up to five years. The NICMOS was the Hubble Space Telescope's first cryogenic instrument. The NICMOS was 2.2 m by 0.88m by 0.88 m (7.1 ft. by 2.8 ft by 2.8 ft) and weighed 390 kg (861 lb).[k] After installation and calibration, STScI managed the NICMOS.
Results	The Hubble Space Telescope enormously improved our understanding of the cosmos, from the universe's size, age, and fate, to the meteorology of planets; it also improved our understanding of stellar births and deaths. More importantly, the Hubble Space Telescope established itself as a premier observatory making discoveries at the forefront of astronomy and becoming "the public's premier gateway to science."[l] See science results above.

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[a] "Pre Launch Mission Operation Report, Hubble Space Telescope–First Servicing Mission," Report no. X 458-61-93-02, November 1993, p. 10 (NASA History Office Folder 005989).

[b] "Quick Facts," HubbleSite, Space Telescope Science Institute, *http://hubblesite.org/reference_desk/facts_.and._figures/quick_facts/quick_facts_2.shtml* (accessed September 7, 2005); The NSSDC Database gives the Hubble Space Telescope's apogee at 610.44 km and perigee at 586.5 km, *http://nssdc.gsfc.nasa.gov/nmc/tmp/1990-037B-traj.html* (accessed September 7, 2005); The "SM2 Media Reference Guide," p 1-6, puts Hubble's orbit at 320 nmi (593 km), *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[c] "STS-31 Press Kit," April 1990, p. 31, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_035_STS-031R_Press_Kit.pdf* (accessed September 12, 2005). Also Chaisson, *The Hubble Wars*, p. 153; "Hubble Amazing Optics," *http://hubblesite.org/sci.d.tech/nuts_.and._bolts/optics/* (accessed April 26, 2006).

[d] "Overview of the Hubble Space Telescope," Space Telescope Science Institute, *http://www.stsci.edu/hst/HST_overview/* (accessed September 5, 2005).

[e] "SM2 Media Guide," p. 1-6, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[f] "STS-31 Press Kit," pp. 9, 11.

[g] "STS-82 Press Kit, Second Hubble Servicing Mission," February 1997, pp. 14–18, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_082_STS-082_Press_Kit.pdf* (accessed September 5, 2005).

[h] "SM2 Media Guide," p. 4-19, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[i] "SM2 Media Guide," p. 1-6, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005).

[j] "Space Shuttle Mission STS-82 Press Kit," February 1997, p. 27, *http://www.jsc.nasa.gov/history/shuttle_pk/pk/Flight_082_STS-082_Press_Kit.pdf* (accessed September 12, 2005).

[k] "SM2 Media Guide," p. 1-6, *http://hubble.nasa.gov/a_pdf/news/SM2-MediaGuide.pdf* (accessed September 12, 2005). The STS-82 Press Kit gives the weight of NICMOS as 347 kg (765 lb).

[l] "The Hubble Space Telescope: Science in the First Decade," *http://hubblesite.org/discoveries/10th/vault/in-depth/science.shtml* (accessed May 8, 2006).

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics

Launch Date/Launch Site	April 5, 1991 / Kennedy Space Center
Date of Reentry	June 4, 2000
Launch Vehicle	STS-37/*Atlantis*
NASA Role	Project management of the observatory and communications, tracking, and data systems; BATSE and EGRET instruments
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	Primary objective: • To obtain two years of gamma-ray measurements (10 KeV to 30 GeV) covering close to the entire celestial sphere, with instruments providing an order-of-magnitude greater sensitivity and accuracy than previously flown gamma-ray missions. Secondary objectives: • To provide a uniform full-sky gamma-ray survey using wide-field imaging instruments and make selected high-priority observations using the narrow aperture and independently oriented instruments. • To provide guest investigators 30 percent of the observation time at the completion of Phase I (first 15 months) and 50 percent of the observation time at the completion of Phase II (an additional 12 months). Specific objectives:[b] • To study gamma-ray sources emitting in our galaxy and beyond. • To investigate evolutionary forces in neutron stars and black holes. • To perform detailed studies of nucleosynthesis. • To search for primordial black hole emissions.
Orbit Characteristics:	
Apogee	453 km (281 mi)
Perigee	448 km (278 mi)
Inclination (deg)	28.5
Period (min)	90
Weight	Fueled: 15,876 kg (35,000 lb)[c]
Dimensions[d]	Launch configuration: 7.72 m by 5.03 m by 4.62 m (25.3 ft by 16.5 ft by 15.2 ft) Orbit configuration (solar arrays and high gain antenna deployed): 9.5 m by 21.52 m by 9.24 m (31.2 ft by 70.6 ft by 30.3 ft) Solar array wing span: 21.52 m (70.6 ft)
Power Source	Solar arrays, three nickel cadmium batteries
Prime Contractor	TRW Space & Electronics Group

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Instruments and Experiments	• BATSE PI: Gerald J. Fishman, Marshall Space Flight Center The BATSE was the all-sky monitor for the observatory, detecting and locating strong transient sources, called gamma-ray bursts, as well as outbursts from other sources across the entire sky. There were eight BATSE detectors, one facing outward from each satellite corner, which were sensitive to gamma-ray energies from 20 keV to more than 1,000 keV. Sodium iodide (NaI) crystals at the heart of the BATSE detectors produced a flash of visible light when struck by gamma rays. The flashes were recorded by light-sensitive detectors whose output signal was digitized and analyzed to determine the arrival time and energy of the gamma ray causing the flash. Each BATSE detector unit consisted of a large-area detector sensitive to faint transient events along with a smaller detector optimized for spectroscopic studies of bright events.[e] • OSSE PI: James Kurfess, Naval Research Laboratory The OSSE consisted of four NaI scintillation detectors sensitive to energies from 50 keV to 10 MeV. Each of these detectors could be individually pointed. This allowed observations of a gamma-ray source to be alternated with observations of nearby background regions. An accurate subtraction of background contamination could then be made. The OSSE observed the energy spectrum of nuclear lines in solar flares, the radioactive decay of nuclei in supernova remnants, and the signature of matter-antimatter (electron-positron) annihilation in the galactic center region.[f] • The EGRET used high-voltage, gas-filled spark chambers to produce images at these high energies. High-energy gamma rays entered the chambers and produced an electron-positron pair of particles causing sparks. The path of the particles was recorded, allowing determination of the direction of the original gamma ray. The particle energies were recorded by a NaI crystal beneath the spark chambers that provided a measure of the original gamma-ray energy.[g]

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Instruments and Experiments	• COMPTEL PI: Volker Schönfelder, Max Planck Institute for Extraterrestrial Physics, Germany The COMPTEL used the Compton Effect and two layers of gamma-ray detectors to reconstruct an image of a gamma-ray source in the energy range from 1 MeV to 30 MeV. Gamma rays from active galaxies, radioactive supernova remnants, and diffuse gamma rays from giant molecular clouds could be studied with this instrument. A liquid scintillator that scattered an incoming gamma-ray photon according to the Compton Effect filled the COMPTEL's upper layer of detectors. This photon was then absorbed by NaI crystals in the lower detectors. The instrument recorded the time, location, and energy of the events in each layer of detectors, making it possible to determine the direction and energy of the original gamma-ray photon and reconstruct an image and energy spectrum of the source.[h] • EGRET PI: Carl E. Fichtel, Goddard Space Flight Center; R. Hofstadter, Stanford University; and K. Pinkau, Max Planck Institute for Extraterrestrial Physics, Germany The EGRET provided the highest energy gamma-ray window for the CGRO. The EGRET's energy range was from 20 million to 30 billion eV. The EGRET was 10 to 20 times larger and more sensitive than previous detectors operating at these high energies. The telescope observed high-energy processes associated with diffuse gamma-ray emissions; gamma-ray bursts; cosmic rays; pulsars; and active galaxies known as blazars.

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Results	The instruments on the CGRO made many discoveries, some expected and some surprising. Some of these discoveries were the following: • The discovery that a second class of gamma-ray-emitting active galactic nuclei, known as Seyfert galaxies, emitted most of their gamma rays at lower energies than previously thought was evidence that such objects might be the source of diffuse gamma rays. • The first detection of the presence and nuclear decay of cobalt 57, an isotope of cobalt thought to have been created during the explosion of a star known as Supernova 1987A, helped confirm the nucleosynthesis theory of how elements heavier than hydrogen and helium were formed and distributed in our galaxy through the evolution of stars. • The all-sky map produced by the EGRET was dominated by emission from interactions between cosmic rays and the interstellar gas along the plane of the Milky Way. Some point sources in this map were pulsars along the plane. Seven pulsars were known to emit in the gamma-ray portion of the spectrum, and five of these gamma-ray pulsars were discovered since CGRO launch. The Crab and Geminga pulsars were found near the galactic anticenter. One of the major EGRET discoveries was the class of objects known as blazars—quasars emitting the majority of their electromagnetic energy in the 30 MeV to 30 GeV portion of the spectrum. These objects, which were at cosmological distances, sometimes appeared to vary on timescales of days. • An all-sky map made by the COMPTEL illustrated the power of imaging in a narrow band of gamma-ray energy, in the light of radioactive aluminum 26. This map revealed unexpectedly high concentrations of radioactive aluminum 26 in small regions. In a COMPTEL image of the galactic anticenter, several interesting objects were visible, including two pulsars, a flaring black hole candidate, and a gamma-ray blazar. • In another map of the galactic center region, scanning observations made by the OSSE revealed gamma-ray radiation from the annihilation of positrons and electrons in the interstellar medium, another line emission. The OSSE recorded the spectrum of a solar flare, yielding direct evidence of accelerated particles smashing into material on the Sun's surface, exciting nuclei then radiating in gamma rays.

Table 4–49. Compton Gamma Ray Observatory Mission Characteristics (Continued)

Results	• One of the BATSE's primary objectives was to study the phenomenon of gamma-ray bursts, brief flashes of gamma rays that occurred at unpredictable locations in the sky. The BATSE's all sky map of burst positions showed that, unlike galactic objects clustering near the plane or center of the galaxy, these bursts came from all directions. A cosmological origin (i.e., well beyond our galaxy) was now established. Burst light curves suggested a chaotic phenomenon was at work; no two have ever appeared exactly the same. An average light curve for bright and dim bursts was consistent with the explanation that bursts were at cosmological distances: the dim ones, which presumably were farther away, were stretched more in cosmic time than the bright ones, as the events participated in the general expansion of the universe. The BATSE also could image the sky, using Earth as an occulting disk, using a technique called Radon transforms.[i]

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[a] "Gamma Ray Observatory Mission Operations Report," NASA Office of Space Science and Applications, Report no. E-S-458-31-91-01, p. 4 (NASA History Office Folder 30780).

[b] "GRO, Compton Gamma Ray Observatory Quicklook," JPL Mission and Spacecraft Library, *http://msl.jpl.nasa.gov/QuickLooks/groQL.html* (accessed August 11, 2005).

[c] "Compton Gamma-Ray Observatory," NSSDC Master Catalog: Spacecraft, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-027B* (accessed August 31, 2005).

[d] Bob Soufl, GRO Description, May 21, 1991, via Martin Davis, Goddard Space Flight Center, e-mail received September 6, 2005.

[e] "The Burst And Transient Source Experiment (BATSE)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/batse.html* (accessed August 31, 2005).

[f] "The Oriented Scintillation Spectrometer Experiment (OSSE)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/osse.html* (accessed August 31, 2005).

[g] "The Energetic Gamma Ray Experiment Telescope (EGRET)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/egret.html* (accessed August 31, 2005).

[h] "The Imaging Compton Telescope (COMPTEL)," *http://cossc.gsfc.nasa.gov/docs/cgro/cgro/comptel.html* (accessed August 31, 2005).

[i] "About the Compton Gamma Ray Observatory," CGRO Science Support Center, *http://cossc.gsfc.nasa.gov/docs/cgro/cgro* (accessed August 31, 2005). Also Donna Drelick, "Compton Gamma Ray Observatory On Orbit Five Years," *Goddard News* 45 (April 1996): 3.

Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics

Launch Date/Launch Site	July 23, 1999 / Kennedy Space Center
Date of Reentry	Currently operating
Launch Vehicle	STS-93/*Columbia*
NASA Role	Mission management
Responsible (Lead) Center	Marshall Space Flight Center
Mission Objectives[a]	Science objectives:[b] • To determine the nature of celestial objects from normal stars to quasars. • To understand the nature of physical processes that take place in and between astronomical objects. • To understand the history and evolution of the universe. Program objective:[c] To address some of the most fundamental and pressing questions in present-day astrophysics through observations of matter at the extremes of temperature, density, and energy content. The Chandra mission scientific objectives are the following: • Determine the nature of celestial objects, from normal stars to quasars. • Understand the nature of physical processes that take place in and between astronomical objects. • Understand the history and evolution of the universe. The AXAF program objectives and philosophy are the following:[d] The objective of the AXAF program is to make fundamental scientific discoveries and contribute to our understanding of the universe through rigorous analysis and distribution of unique scientific data. The AXAF program will accomplish this objective by extending the range of astrophysical observations significantly beyond that of previous x-ray observatories through increases in sensitivity and resolution.
Orbit Characteristics:	
Apogee	140,161 km (86,900 mi)
Perigee	10,000 km (6,213 mi)
Inclination (deg)	28.5
Period	64 hours, 18 minutes
Weight	Dry: 4,800 kg (10,560 lb); total at launch: 12,930 lb
Dimensions	13.8 m by 19.5 m (45.3 ft by 64.0 ft) (solar arrays deployed)
Power Source	Solar arrays and nickel hydrogen batteries
Prime Contractor	TRW, Inc. (Northrop Grumman)

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Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics (Continued)

Instruments and Experiments	• ACIS PI: Gordon Garmire, Pennsylvania State University One of two focal plane instruments, the ACIS is an array of charged coupled devices. This instrument can make x-ray images and, at the same time, measure the energy of each incoming x-ray. Thus, scientists can make pictures of objects using only x-rays produced by a single chemical element and compare, for example, the appearance of a supernova remnant in light produced by oxygen ions to that of neon or iron ions. The ACIS is the instrument of choice for studying temperature variations across x-ray sources such as vast clouds of hot gas in intergalactic space or chemical variations across clouds left by supernova explosions. • HRC PI: Stephen Murray, Harvard-Smithsonian Center for Astrophysics The HRC is one of two instruments used at the focus of the Chandra where it detects x-rays reflected from an assembly of eight mirrors. The camera's unique capabilities stem from the close match of its imaging capability to the focusing power of the mirrors. When used with the Chandra mirrors, the HRC can make images that reveal details as small as one-half an arc second. The HRC is especially useful for imaging hot matter in remnants of exploded stars, distant galaxies, and clusters of galaxies. The camera also is useful for identifying very faint sources. • The High Energy Transmission Grating Spectrometer and the Low Energy Transmission Grating Spectrometer

Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics (Continued)

Instruments and Experiments	• These spectrometers are dedicated to high-resolution spectroscopy. Each spectrometer is activated by swinging an assembly into position behind the mirrors. The assembly holds hundreds of gold transmission gratings; when in place behind the mirrors, the gratings intercept the x-rays reflected from the mirrors. These gratings diffract the intercepted x-rays, changing their direction by amounts that depend sensitively on the x-ray energy, much like a prism separates light into its component colors. One of the focal plane cameras, either the HRC or ACIS, detects the location of the diffracted x-ray, enabling a precise determination of its energy. The gratings exploit the Chandra's sharp mirror focus and matching detector resolution to produce high resolution x-ray spectroscopy. Since the grating spectrometers can measure energy to an accuracy of up to one part in a thousand, they are used to study detailed energy spectra, distinguishing individual x-ray lines. This enables the temperature, ionization, and chemical composition to be explored. • LETG PI: (Development) A.C. Brinkman, University of Utrecht; (Operations) Mariano Mendez, Netherlands Institute for Space Research The LETG is a freestanding gold grating made of fine wires or bars with a regular spacing, or period, of 1µm. The fine gold wires are held by two different support structures, a linear grid with 25.4-µm spacing and a coarse triangular mesh with 2-mm (0.08-in) spacing. The gratings are mounted on a toroidal ring structure matched to the Chandra mirrors. The LETG gratings are designed to cover an energy range from 0.08 keV to 2 keV. However, their diffraction can also be seen in visible light.

Table 4–50. Advanced X-Ray Astrophysical Facility (Chandra) Mission Characteristics (Continued)

Instruments and Experiments	• HETG PI: Claude R. Canizares, MIT Center for Space Research The HETGs have much finer periods, as follows: 0.2 μm or 2,000 angstroms for the high-energy gratings, and 0.4μm or 4,000 angstroms for the medium energy gratings. To distinguish between them, the two types of gratings are oriented at slightly different angles so that the x-rays are diffracted in an "X" pattern at the focal plane. Since the size of the gold grating bars is smaller than a wavelength of visible light, special fabrication techniques were required to make them. The gratings take advantage of the fact that the gold bars are partially transparent to x-rays, so that the diffraction is more efficient, and more x-rays are captured in the high-resolution spectrum. The HETG gratings are designed to cover an energy range from 0.4 to 10 keV.
Results	Successful launch in 1999 after more than 20 years of development.
Remarks	The Chandra is the world's most powerful x-ray telescope. With its inertial upper stage and support equipment, the Chandra was the largest and heaviest payload ever launched by the Space Shuttle. The Chandra's operating orbit is 200 times higher than the Hubble Space Telescope's orbit. On each orbit, the Chandra observatory travels one-third of the way to the Moon.

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[a] E-mail from David Hood, NASA Marshall Space Flight Center, October 7, 2005.

[b] "Program Plan for Advanced X-ray Astrophysics Facility Design, Development, and Operations," April 17, 1997.

[c] "Program Commitment Agreement," Chandra X-ray Observatory, February 2003.

[d] "Advanced X-ray Astrophysics Facility Program Policy and Requirements Document, Level I," April 20, 1994.

Table 4–51. Ulysses Mission Milestones[a]

Date	Event
October 6, 1990	Launch on the Space Shuttle *Discovery*
December 30, 1990	1st opposition[b]
August 21, 1991	1st conjunction[c]
February 8, 1992	Jupiter closest approach
February 15, 1992	1st aphelion
February 27, 1992	2nd opposition
August 26, 1992	Maximum Earth range
September 2, 1992	2nd conjunction
March 1, 1993	3rd opposition
September 4, 1993	3rd conjunction
June 26, 1994	Start of first south polar pass
September 13, 1994	Maximum south solar latitude
November 5, 1994	End of first south polar pass
March 4, 1995	4th conjunction
March 12, 1995	1st perihelion
March 13, 1995	Ecliptic crossing
June 9, 1995	Minimum Earth range
June 19, 1995	Start of first north polar pass
July 31, 1995	Maximum north solar latitude
September 29, 1995	End of first north polar pass
February 24, 1997	4th opposition
August 30, 1997	5th conjunction
February 26, 1998	5th opposition
April 17, 1998	2nd aphelion
May 9, 1998	Ecliptic crossing
August 28, 1998	Maximum Earth range
September 1, 1998	6th conjunction

[a] "Ulysses Mission Milestones," *http://ulysses-ops.jpl.esa.int/ulsfct/milestones1.html* (accessed August 25, 2005).

[b] The term *opposition* describes an alignment of Earth, the Sun, and spacecraft with Earth in the middle.

[c] The term *conjunction* as used in the Ulysses mission refers to a "superior conjunction," an alignment of Earth, the Sun, and spacecraft with the Sun in the middle and Earth and spacecraft on opposite sides of it.

Table 4–52. Ulysses Mission Characteristics

Launch Date/Launch Site	October 6, 1990 / Kennedy Space Center
Date of Reentry	Mission ended July 1, 2008.
Launch Vehicle	STS-41/*Discovery*
NASA Role	Launch vehicle and launch support, inertial upper stage, payload assist module
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	Primary mission objective: • To investigate for the first time, as a function of solar latitude, the properties of the solar wind; the structure of the Sun/wind interface; the heliospheric magnetic field; solar radio bursts and plasma waves; solar x-rays; solar and galactic cosmic rays; and interstellar interplanetary neutral gas and dust. Secondary objectives: • To conduct interplanetary-physics investigations during the in-ecliptic Earth-Jupiter phase; measure the Jovian magnetosphere during the Jupiter flyby phase; detect cosmic gamma-ray bursts; and search for gravitational waves from cataclysmic cosmic events. Science objectives: • To provide an accurate assessment of the global three-dimensional properties of the interplanetary magnetic field and the solar wind. • To improve our knowledge of the composition of the solar atmosphere and the origin and acceleration of the solar wind by systematically studying the composition of the solar-wind plasma and solar energetic particles at different heliographic latitudes. • To provide new insight into the acceleration of energetic particles in solar flares and into the storage and transport of these particles in the corona by observing the x-ray and particle emission from solar active regions and from other magnetic configurations that are more accessible for study from out-of-the-ecliptic. • To further our knowledge of the internal dynamics of the solar wind; our knowledge of the waves, shocks, and other discontinuities; and our knowledge of the heliospheric propagation and acceleration of energetic particles by sampling plasma conditions expected to differ from those available for study near the ecliptic. • To improve our understanding of the spectra and composition of galactic cosmic rays in interstellar space by measuring the solar modulation of these particles as a function of heliographic latitude and by sampling these particles over the solar poles, where low-energy cosmic rays may have easier access to the inner solar system than near the ecliptic plane.

Table 4–52. Ulysses Mission Characteristics (Continued)

Mission Objectives[a]	• To advance our knowledge of the neutral component of interstellar gas by measuring, as a function of heliographic latitude, the properties and distribution of neutral gas entering the heliosphere. • To improve our knowledge of interplanetary dust by measuring its properties and distribution as a function of heliographic latitude. • To search for gamma-ray burst sources and, in conjunction with other spacecraft observations, identify these sourced with known celestial objects or phenomena. • To search for low-frequency gravitational waves by recording very precise two-way Doppler tracking data at the ground stations.
Orbit Characteristics	Solar orbit inclined at 80 degrees to the ecliptic plane
Period	6.2 years around the Sun[b]
Weight	366.7 kg (808.4 lb) total at launch; scientific payload: 55.1 kg (121.5 lb)[c]
Dimensions	Length: 3.2 m (10.5 ft), width: 3.3 m (10.8 ft) (booms stowed), height: 2.1 m (6.9 ft)
Power Source	Radioisotope thermoelectric generator
Prime Contractor	Dornier Systems
Instruments and Experiments	• Magnetic Fields Experiment (VHM/FGM) PI: Andrew Balogh, Imperial College, the United Kingdom This experiment determined the large-scale features and gradients of the field, as well as the heliolatitude dependence of interplanetary phenomena so far only observed near the ecliptic plane. The magnetometer used two sensors, a Vector Helium Magnetometer and a Fluxgate Magnetometer. On-board data processing yielded measurements of the magnetic field vector with a time resolution up to two vectors per second and a sensitivity of about 10 pT. • Solar Wind Plasma (SWOOPS) Experiment PI: D.J. McComas, Los Alamos National Laboratory This experiment detected and analyzed particles in the solar wind to determine variations in the particles from the equator to the poles. It determined how the solar wind changed as a function of distance from the Sun and distance from the ecliptic plane. While traveling along its flight path, the SWOOPS Experiment also measured local changes in the number and energy of particles as the solar wind blew past Ulysses. The instrument measured how the properties of the solar wind differed between low and high latitudes. The instrument traced the solar wind back to its place of origin more easily at the poles than at the equator. It observed particles in the energy range from 1 eV to 35,000 eV.

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Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• SWICS PIs: George Sloeckler, University of Maryland and Johannes Geiss, Universitt, Switzerland The SWICS determined the elemental and ionic-charge composition and the temperatures and mean speeds of all major solar-wind ions, from hydrogen through iron, at solar wind speeds ranging from 175 km/s to 1,280 km/s (109 mi/s to 795 mi/s). The instrument, which covered an energy-per-charge range from 0.16 keV/e to 59.6 keV/e in approximately 13 minutes, combined an electrostatic analyzer with post-acceleration, followed by a time-of-flight and energy measurement. • Unified Radio and Plasma Wave (URAP) Investigation: PI: R.J. MacDowall Goddard Space Flight Center The URAP Investigation determined the direction, angular size, and polarization of radio sources for remote sensing of the heliosphere and the Jovian magnetosphere. The investigation also conducted a detailed study of local wave phenomena, which determine the transport coefficients of the ambient plasma. The URAP Investigation sensors consisted of a 72.5-m (237.9-ft) electric field antenna in the spin plane, a 7.5-m (24.6-ft) electric field monopole along the spin axis, and a pair of orthogonal search coil magnetic antennae. The various receivers, designed to encompass specific needs of the investigation, covered the frequency range from dc to 1 MHz. A relaxation sounder provided very accurate electron density measurements. • Energetic Particle Composition and Neutral Gas Experiment (EPAC)[d] PI: Erhardt Keppler, Max Planck Institut für Aeronomie, Germany The EPAC provided information on the relative abundances; energies; direction of travel; and chemical composition of medium-energy charged particles in interplanetary space. The EPAC consisted of four identical telescopes inclined at angles of 22.5°, 67.5°, 112.5°, and 157.5° with respect to the spacecraft spin axis. Each telescope's FOV was 35° full angle. A separate instrument detected neutral helium atoms entering the solar system from interstellar space and determined their speed; direction of arrival; temperature; and density.

Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies (HI-SCALE) PI: Louis J. Lanzerotti, Bell Laboratories, Lucent Technologies The HI-SCALE measured interplanetary ions and electrons during the entire mission. Ions and electrons were identified uniquely and detected by five separate solid-state detector telescopes oriented to give nearly complete pitch-angle coverage from the spinning spacecraft. Ion elemental abundances were determined by a delta E vs. E telescope using a thin (5-micron) front-facing solid state detector element in a three-element telescope. A microprocessor-based data system controlled experiment operation. Inflight calibration was provided by radioactive sources mounted on telescope covers that could be closed for calibration purposes and for radiation protection during the mission. Ion and electron spectral information was determined using both broad-energy-range rate channels and a 32-channel pulse-height analyzer for more detailed spectra. The instrument weighed 5.775 kg (12.7 lb) and used 4.0 W of power. • Cosmic Ray and Solar Particle Investigation (COSPIN) PI: R.B. McKibben, University of Chicago The COSPIN consisted of a group of six charged-particle telescopes to measure the energy, composition, intensity, and anisotropy of nucleons in the energy range from ~0.5 MeV/nucleon to ~600 MeV/nucleon for elements in the range H to Ni. Isotopic abundances for nuclei H to Ni were obtained over a more limited energy range. Electron measurements extended from 2.5 MeV to 6,000 MeV. One set of telescopes measured the three-dimensional anisotropies of protons and helium at low energies. A special high-flux telescope provided measurements of protons and heavier particles ~0.2 MeV to ~36 MeV with high azimuthal resolution. An international consortium prepared these instruments to address a wide range of scientific objectives.

Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• Solar X-rays and Cosmic Gamma Ray Bursts PI: Kevin Hurley, University of California, Berkeley This experiment detected x-rays emitted sporadically from the vicinity of solar active regions. Although solar x-rays were observed for many years by spacecraft above Earth's atmosphere, the altitude in the solar atmosphere at which the radiation was emitted and its directivity, which would help identify the source mechanism, were unknown. As Ulysses traveled poleward, the Sun blocked radiation at low altitudes and affected how the intensity varied with direction to the source. Cosmic gamma-ray bursts were detected about 20 years ago, but their origin remained obscure. By accurately timing their arrival at Ulysses and at Earth, their source location could be pinpointed to see what astrophysical objects or bodies gave rise to them. • Dust Experiment (DUST) PI: Eberhard Grün, Max Planck Institut für Kernphysik, Germany The DUST directly observed dust grains with masses between 10^{-16} g and 10^{-6} g in interplanetary space to investigate their physical and dynamical properties as functions of heliocentric distance and ecliptic latitude. Of special interest was the question of what portion was provided by comets, asteroids, and interstellar particles. The investigation was performed with an instrument measuring the mass, speed, flight direction, and electric charge of individual dust particles. The instrument was a multicoincidence detector with a mass sensitivity 10^6 times higher than that of previous *in situ* experiments that measured dust in the outer solar system. The instrument weighed 3.8 kg (8.4 lb), consumed 2.2 W, and had a normal data transmission rate of 8 bits/s in nominal spacecraft tracking mode. • Coronal-Sounding Experiment (SCE) PI: M.K. Bird, University of Bonn, Germany The SCE used established coronal-sounding techniques to derive the plasma parameters of the solar atmosphere. Applying appropriate model assumptions, the three-dimensional electron density distribution was determined from dual-frequency ranging and Doppler measurements recorded at the NASA Deep Space Network (DSN) during solar conjunctions. Multistation observations were used to derive the plasma bulk velocity at solar distances where the solar wind was expected to undergo its greatest acceleration. As a secondary objective profiting from the favorable geometry during the Jupiter encounter, radio-sounding measurements yielded a unique cross-scan of electron density in the Io Plasma Torus.

Table 4–52. Ulysses Mission Characteristics (Continued)

Instruments and Experiments	• Gravitational Waves Experiment (GWE) PI: Bruno Bertotti, Universita di Pavia, Italy The GWE used the Ulysses radio transmitter for scientific purposes. According to Einstein's theory of relativity, the motion of large masses in the universe—such as those associated with the formation of black holes—should cause the radiation of gravitational waves. Though such waves had yet to be detected, they could be observed through their effect on the spacecraft, which was expected to undergo a slight perturbation that might be detected as a shift in frequency of the Ulysses radio signal. Interdisciplinary topics:[e] • Directional Discontinuities Team Leader: Joseph Lemaire, Institut d'Aeronomie Spatiale de Belgique, Belgium This experiment compared Ulysses measurements of solar-wind plasma and magnetic field regions to theoretical models. • Mass Loss and Ion Composition Team Leader: Giancarlo Noci, Istituto de Astronomia, Italy This experiment combined measurements of the solar wind and magnetic field to study the mass and angular momentum lost by the Sun in the equatorial and polar regions. The experiment also studied the dependence of the solar wind composition on solar latitude.
Results	Ulysses explored the solar wind from all angles, producing the first three-dimensional picture of the heliosphere. The mission found that the wind from the cooler regions close to the Sun's poles fans out to fill two-thirds of the heliosphere and blows at a uniform speed of 750 km/s (466 mi/s), much faster than the 350 km/s (217 mi/s) wind that emerges from the Sun's equatorial zone. Ulysses was the first spacecraft to survey the Sun's southern and northern polar regions.[f] See the narrative above for further mission results.

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[a] "Ulysses Mission Operation Report," Report no. S-448-41-90-01, October 4, 1990 (NASA History Office Electronic Document, Record no. 30797).

[b] "Ulysses Orbit/Navigation," European Space Agency, *http://helio.estec.esa.nl/ulysses/resources_galleryorbit.html* (accessed August 25, 2005).

[c] "Ulysses Datasheet," *http://ulysses-ops.jpl.esa.int/ulsfct/datasheet.html* (accessed August 25, 2005).

[d] Title of experiment as given in "Space Shuttle Mission STS-41 Press Kit," October 1990, p. 15. Title of experiment is given as "Energetic Particle Composition and Interstellar Gas" in the "Ulysses Mission Operation Report," Office of Space Science and Applications, Report no. S-448-41-90-01, October 4, 1990.

[e] "STS-41 Press Kit," p. 17.

[f] "Ulysses Overview," *http://www.esa.int/esaSC/120395_index_0_m.html* (accessed October 20, 2005).

Table 4–53. ASCA/Astro-D Mission Characteristics

Launch Date/Launch Site	February 20, 1993 / Kagoshima Space Center, Japan
Date of Reentry	March 2, 2001; lost attitude control on July 14, 2000, during a geomagnetic storm, ending scientific observations.
Launch Vehicle	ISAS M-3S-II
NASA Role	Provided four telescope mirrors and two x-ray CCD solid state detectors; telemetry tracking support via the DSN; pre-mission test support and mission support
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To examine a variety of x-ray sources with moderate spatial and spectral resolution at energies from 1 keV to 12 keV, with particular emphasis on the iron K band near 6 keV. • To study the structure of extended sources such as clusters of galaxies and supernova remnants. • To determine temperatures and elemental abundances in astrophysical sources through the measurement of spectral features.
Orbit Characteristics:	
Apogee	500 km (311 mi)
Perigee	600 km (373 mi)
Inclination (deg)	31.5
Period (min)	95
Weight	417 kg (919 lb)
Dimensions	4.7 m (15.4 ft) along the telescope axis, 3.5 m (11.5 ft) across the solar paddles
Power Source	Solar panels and batteries
Prime Contractor	NEC under contract to the ISAS
Instruments and Experiments	• XRT (4) PI: Peter Serlemitsos, Goddard Space Flight Center The ASCA XRTs were lightweight versions of similar mirrors flown earlier on the Broad Band X-ray Telescope (BBXRT) experiment aboard NASA's Astro-1 Shuttle mission.[b] Two identical XRTs worked in conjunction with GISs and two worked with SISs. The XRTs were developed by the ISAS and used four sets of multi-nested thin-foil conical reflectors provided by NASA.

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Instruments and Experiments	Each conical foil, x-ray mirror on the ASCA consisted of 120 nested, gold-coated, aluminum foil surfaces. The conical geometry approximated of the more precise Wolter type I geometry for grazing incidence mirrors; this was crucial because it allowed the mirrors to be constructed of thin foil. The mirror technology provided a large throughput through high energies. The effective area was greater than 1,000 cm^2 below 2 keV and greater than 500 cm^2 around 6 keV to 7 keV.[c] The mirrors were equipped with heating elements to elevate their mean temperature in orbit; this ensured that the reflecting surfaces remained free of any condensable materials that might escape from the rest of the spacecraft and guarded against large thermal gradients across the mirror structure that could defocus the mirror. Additionally, very thin (0.22 m (0.7 ft) and 0.54 m (1.8 ft) for the SIS and GIS detectors, respectively) aluminized mylar thermal covers were fastened over the entire mirror aperture. The mirrors were mounted on an extendable optical bench that was commanded to extend 1,200 mm (47 in) after launch to increase the mirror-to-detector distance to the nominal 3,500 mm (138 in) focal length. During integration at the spacecraft, the fields of view of the four telescopes were co-aligned to within less than 1 arc minute.[d] • GIS (2)[e] PI: Kazuo Makishima, University of Tokyo The two GISs were imaging gas scintillation proportional counters, each with a gas cell and a photon-sensitive phototube. They were based on the gas scintillation proportional counter that flew on Japan's second x-ray astronomy mission TENMA. The gas cell was filled with a mixture of 90 percent xenon and 10 percent helium, and it had a front window made of beryllium 10 microns thick. The phototube had a quartz window 7.5 cm (2.9 in) thick and 10-stage dynodes. The area sensitive to x-rays was 50 mm (2 in) in diameter. It had an energy range from 0.7 keV to 10 keV, energy resolution of 8 percent at 5.8 keV, and a circular FOV with a diameter of 50 arc minutes. Scientists and engineers at Tokyo University built the GIS.

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Instruments and Experiments	• SIS (2) PI: George Ricker, Massachusetts Institute of Technology The two SISs were identical independent CCD camera systems provided by a hardware team from MIT, Osaka University, and the ISAS. Each module had a hybrid CCD at the focus of a grazing incidence thin-foil telescope. Each camera was based around four 420-pixel by 422-pixel CCD chips, abutted side-by-side, front-side illuminated, and operated in frame-store configuration. The SIS had an energy range of 0.4 keV to 10 keV; its energy resolution was 2 percent at 5.9 keV. The SIS had a 22-arc minute by 22-arc minute square FOV.[f]
Results	The ASCA scientists made significant discoveries relating to magnetars, black holes, and cosmic rays. • The discovery of a neutron star, located 40,000 light years from Earth, confirmed the existence of a special class of neutron stars called “magnetars,” objects with magnetic fields estimated to be one thousand trillion times the strength of Earth’s magnetic field. The finding should help astronomers better calculate the rate at which stars die and create the heavier elements that later become planets and other stars.[g] • Measurements made with the ASCA, as well as with other satellites, contributed to evidence that some recently discovered black holes “vacuum up” energy from their surroundings through their “event horizons,” the one-way membrane around black holes predicted by Einstein’s theory of relativity. Analysis of a particular x-ray nova called V404 Cyg indicated that the star seemed to be swallowing nearly a hundred times more energy than it radiated, and the only way this could happen was if the star was a true black hole. This was the most real, direct evidence of black holes that scientists have had.[h] Astronomers working with ASCA data found an indicator of the rate at which giant black holes at the centers of distant galaxies were swallowing matter from their surroundings. The indicator consisted of x-ray emissions from very energetic iron atoms swirling in toward the edge of the black hole.[i]

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Results	• Physicists from Japan and the United States used ASCA data to discover a possible solution to the puzzle of the origin of high-energy cosmic rays that bombard Earth from all directions in space. They found what they termed “the first strong observational evidence” for the production of these particles in the shock wave of a supernova remnant, the expanding fireball produced by the explosion of a star. The investigators used the satellite to determine that cosmic rays were generated at a high rate in the remains of the supernova discovered in the year 1006 AD, which appeared to medieval viewers to be as bright as the Moon. They determined that the cosmic rays were accelerated to high velocities by a process first suggested by the nuclear physicist Enrico Fermi in 1949.[j] Scientific discoveries were made in the following areas:[k] • Origin of the diffuse x-ray background. • Active galactic nuclei including the first direct detection of relativistic line broadening of an x-ray emission line in an active galactic nucleus, indicating that the observed iron K line radiation emanated from within tens of Schwarzschild radii of the massive central object. Also detected x-ray emissions from the radio lobes of Fornax A and Centaurus B. • Clusters of galaxies including highly robust determinations of the mass of clusters of galaxies and the demonstration that most of the intracluster gas in rich clusters had been processed by Type II supernovae at early epochs. • Galaxies (and galactic center) including the discovery that metal abundances in the gas haloes of elliptical galaxies were sub-solar with, in the few cases measured so far, a decrease in abundance with radius. Also evidence that the center of the Milky Way was filled with ionized hot gas whose heating mechanism remains unknown. • Supernova remnants including the measurement, using images in prominent x-ray emission lines, of significant variation in supernova remnants of both ionization and chemical composition as a function of position, as well as coherent velocity features directly measuring the expansion of the ejecta; the identification of a site of cosmic ray acceleration in the supernova remnant SN1006. • Stars including measurements of abundances in the coronae of active stars suggesting metal deficiencies when compared to photospheric abundances. Also the unexpected discovery of hard x-ray emissions, including a flare, from class I protostellar candidates.

Table 4–53. ASCA/Astro-D Mission Characteristics (Continued)

Results	• X-ray binaries including the discovery of a ~30 msec period in Cen X-4, demonstrating the theoretically predicted link between low-mass x-ray binaries and radio millisecond pulsars. • Cataclysmic variables and supersoft sources. • Gamma-ray bursts including the identification of a soft gamma-ray repeater with a neutron star in a supernova remnant.

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[a] "ASTRO-D Mission Operation Report," Report no. S-689-93-01 (NASA History Office Folder 5670).

[b] Peter J. Serlemitsos and Hideyo Kunieda, "The ASCA Mirrors," *http://agile.gsfc.nasa.gov/docs/asca/newsletters/mirrors1.html* (accessed August 29, 2005).

[c] "ASTRO-D Mission Operation Report," Report no. S-689-93-01, pp. 6–7 (NASA History Office Folder 5670).

[d] Peter J. Serlemitsos and Hiedyo Kunieda, "The ASCA Mirrors," *http://agile.gsfc.nasa.gov/docs/asca/newsletters/mirrors1.html* (accessed May 4, 2006).

[e] "ASCA's Gas Imaging Spectrometers," *http://agile.gsfc.nasa.gov/docs/asca/asca_gis.html* (accessed August 29, 2005). PIs provided by Nicholas White, ASCA Project Scientist, in an e-mail, May 3, 2006.

[f] "ASCA's Solid-state Imaging Spectrometers," *http://agile.gsfc.nasa.gov/docs/asca/asca_sis.html* (accessed September 26, 2005).

[g] "Strongest Stellar Magnetic Field Yet Observed Confirms Existence of Magnetars," *NASA News* Release 98-87, May 20, 1998, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1998/98-087.txt* (accessed May 4, 2006).

[h] "Astronomers Closing in on Black Holes," Harvard–Smithsonian Center for Astrophysics, (no date), *http://sao-www.harvard.edu/blackhole/index.html* (accessed September 25, 2005).

[i] "Astronomers Discover Indicator That Reveals Rate of Matter Consumption by Enormous Black Holes," ASCA Guest Observer Facility, Release no. 97-141, October 27, 1997, *http://heasarc.gsfc.nasa.gov/docs/asca/science/nandra.html* (accessed September 26, 2005).

[j] "Cosmic Ray Mystery May Be Solved," *NASA News* Release 95-208, November 21, 1995, *ftp://ftp.hq.nasa.gov/pub/pao/pressrel/1995/95-208.txt* (accessed September 25, 2005).

[k] K.A. Arnaud et al, "ASCA Science Highlights," *http://legacy.gsfc.nasa.gov/docs/asca/science/science.html* (accessed August 29, 2005).

Table 4–54. BeppoSAX Mission Characteristics

Launch Date/Launch Site	April 30, 1996 / Cape Canaveral
Date of Reentry	Reentered April 29, 2003, based on American Space Surveillance Network assessment; switched off April 11, 2002.[a]
Launch Vehicle	Atlas-Centaur
NASA Role	Launch vehicle and launch site, data archive
Mission Objectives	Scientific objectives:[b] • To observe x-ray sources in the range from 0.1 keV to 300 keV over a relatively large area. • To monitor large regions of the sky with a resolution of 5 arc minutes in the range from 2 keV to 30 keV to study long-term variability of sources down to 1 mCrab; also to detect x-ray transient phenomena.
Orbit Characteristics:	
Apogee	594 km (369 mi)
Perigee	575 km (357 mi)
Inclination (deg)	3.9
Period (min)	96.4
Weight	900 kg (1,984 lb) (on-orbit dry mass), 1,400 kg (3,086 lb) total
Dimensions	Diameter: 2.7 m (8.9 ft) (solar panels closed); height: 3.6 m (11.8 ft)
Power Source	Solar panels
Prime Contractor	Alena Spazio (space segment) Telespazio (ground segment)
Instruments and Experiments	• Narrow Field Instruments: Four x-ray imaging concentrators sensitive from 1 keV to 10 keV (one extending down to 0.1 keV). The instrumentation consisted of the following: — Medium Energy Concentrator Spectrometer (MECS): Medium-energy set (from 1.3 keV to 10 keV) of three identical grazing-incidence telescopes with double cone geometry. The effective area was a total of 150 cm^2 (23 sq in) at 6 keV; the FOV was 56 arc minutes in diameter, and the angular resolution for 50 percent total signal radius was 75 arc seconds at 6 keV. — Low Energy Concentrator Spectrometer (LECS): Low-energy (from 0.1 keV to 10 keV) telescope, identical to the other three but with a thin window position sensitive gas scintillation proportional counter in its focal plane; the effective area was 22 cm^2 (3.4 sq in) at 0.28 keV; the FOV was 37 arc minutes diameter, and the angular resolution was 9.7 arc minutes at 0.28 keV.

Table 4–54. BeppoSAX Mission Characteristics (Continued)

Instruments and Experiments	— High Pressure Gas Scintillator Proportional Counter: Energy from 4 keV to 120 keV; the effective area was 240 cm^2 (37 sq in) at 30 keV. • Phoswich Detection System (PDS): Had a range of 15 keV to 300 keV. The lateral shields of the PDS were used as a gamma-ray burst monitor in the range from 60 keV to 600 keV. The effective area was 600 cm^2 (93 sq in) at 80 keV • WFCs: Two cameras ranged from 2 keV to 30 keV with FOVs of 20 degrees by 20 degrees. The WFCs were perpendicular to the axis of the narrow field instruments and pointed in opposite directions to each other. The effective area was 140 cm^2 (22 sq in).
Results	During its six years of active life, BeppoSAX made 30,720 contacts with the ESA's Malindi ground station in Kenya and performed nearly 1,500 observations of most types of cosmic sources, discovering more than 50 gamma-ray bursts.

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[a] "BeppoSAX Status," *http://heasarc.gsfc.nasa.gov/docs/sax/email/sax_status.html#11apr2002* (accessed August 3, 2005).

[b] "BeppoSAX Mission Outline," The BeppoSAX Science Data Center, *http://bepposax.gsfc.nasa.gov/bepposax/scientificase.html* (accessed August 3, 2005).

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics

Launch Date/Launch Site	October 24, 1998 / Cape Canaveral Air Station
Date of Reentry	Deep Space 1 mission ended December 18, 2001, when transmitter was turned off.
Launch Vehicle	Delta II 7326 (first use of this model)
NASA Role	Project management
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	Deep Space 1: To test 12 advanced technologies in deep space; to lower the cost and risk to future science-driven missions using the technologies for the first time.
Orbit Characteristics	Deep space orbit
Weight	Deep Space 1: Total: 486.3 kg (1,072.1 lb), spacecraft: 373.4 kg (823.2 lb), hydrazine: 31.1 kg (68.6 lb), xenon: 81.5 kg (179.7 lb)
Dimensions	Deep Space 1: Bus: 1.1 m by 1.1 m by 1.5 m (3.6 ft by 3.6 ft by 4.9 ft) With instruments and systems attached: 2.5 m (8.2 ft) high, 2.1 m (6.9 ft) deep, 1.7 m (5.5 ft) wide Solar panels: 11.75 m (38.5 ft) deployed
Shape	Octagonal
Power Source	Solar panels and batteries
Prime Contractor	Spacecraft: Spectrum Astro, Inc. Engine: Hughes Electron Dynamics Division, Spectrum Astro, Inc.
Instruments and Experiments	Advanced Technologies: • Solar Electric Ion Propulsion System Developed by Hughes Electron Dynamics Division, Spectrum Astro, Inc., Moog, Inc., and Physical Science, Inc. Unlike chemical rocket engines, ion engines accelerate nearly continuously, giving each ion a tremendous burst of speed. The Deep Space 1 Ion Propulsion System engine provided about 10 times the specific impulse (ratio of thrust to propellant used) of chemical propulsion. — Diagnostic Subsystem PI: Karl-Heinz Glassmeier The primary objective was to monitor and characterize the induced environment around the spacecraft created by the Ion Propulsion System and its interaction with the space environment.

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics (Continued)

Instruments and Experiments	• Solar Concentrator Arrays Developed by AEC-Able Engineering, Inc., Entech, Lewis Research Center, and JPL The arrays provided power to the ion engine more efficiently than conventional arrays and costed and weighed less. The array had to work correctly immediately after launch for the mission to proceed because stored battery energy was sufficient only for a few hours. Autonomy • Autonomous Optical Navigation Developed by JPL This navigation system computed and corrected the spacecraft's course using images of asteroids and stars collected by the on-board camera system. Earlier spacecraft navigation systems relied on human controllers on Earth. • Beacon Monitor Operations Developed by JPL This technology will eventually reduce the need for mission controllers on Earth to monitor the health of the spacecraft at all times. The spacecraft's beacon monitor could beam one of four signals to Earth summarizing its status and indicating the urgency of need for human intervention. • Autonomous Operations System (Remote Agent) Developed by Ames Research Center, JPL, and Carnegie Mellon University This system was composed of an "agent" that could plan, make decisions, and operate by itself. Sophisticated software was programmed into the spacecraft's computer to allow it to think and act on its own without human intervention or guidance. The agent also knew when a failure had occurred, what to do about it, and when to call for help. Science Instruments • Miniature Camera and Imaging Spectrometer PI: Lawrence A. Soderblom, U.S. Geological Survey This instrument was about 10 times less in mass, cost, and power consumption than conventional instruments performing similar tasks. Comparative imaging was done with a standard CCD and a new active pixel sensor, which integrated the electronics and detector on a fingernail-sized chip. The mass of this instrument, which was considered a space physics package, was less than 25 percent of currently used comparable instruments. The instrument required about 50 percent less power than conventional instruments.

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics (Continued)

Instruments and Experiments	• Plasma Experiment for Planetary Exploration (PEPE) PI: David T. Young, Southwest Research Institute This multiple-instrument package measured the three-dimensional mass-resolved plasma distribution. The PEPE collected scientific data during cruise and asteroid encounter; measured the effects induced by the ion propulsion system on the space environment, including interactions with the solar wind and on spacecraft surfaces and instruments; and validated new plasma sensor technologies for use on future flights. The PEPE was mounted on the edge of the octagonal top of Deep Space 1.
	Telecommunications • Small Deep-Space Transponder Developed by Motorola Government Space System This was a miniaturized 3.2-kg (7-lb) transponder combining receiver, command detector, telemetry modulation exciters, beacon tone generation, and control functions. The transponder received and transmitted in the microwave X-band and transmitted in the higher-frequency Ka-band. The transponder's small size and low mass was enabled by the use of advanced gallium arsenide monolithic microwave integrated-circuit chips, high-density packaging techniques, and silicon application-specific integrated-circuit chips. • Ka-Band Solid-State Power Amplifier Developed by Lockheed Martin This high-frequency, solid-state amplifier amplified the transponder radio signal and allowed the spacecraft's transponder to transmit in the microwave Ka band. A system with similar capability using current technology would be more than twice as heavy and three times more expensive.
	Microelectronics • Low-Power Electronics Developed by Lincoln Laboratory, Massachusetts Institute of Technology This experiment involved sophisticated low-voltage technologies, low-activity logic, low-energy architectures, and micro-power management. It tested a ring oscillator, transistors, and a multiplier designed to consume very little electrical power.

Table 4–55. Deep Space 1/SEDSAT Mission Characteristics (Continued)

Instruments and Experiments[a]	• Multifunctional Spacecraft Structure Developed by the U.S. Air Force Phillips Laboratory and Lockheed Martin This multifunctional structure integrated electronics with the spacecraft and demonstrated futuristic technologies for making the spacecraft smaller, lighter, and more efficient. It combined thermal management and electronics in one load-bearing structural element consisting of a composite panel with copper polyimide patches bonded to one side and embedded heat-transferring devices. The panel's outer surface acted as a thermal radiator. Electrical circuitry was designed in the copper polyimide layer; flex jumpers served as electrical interconnects for power distribution and data transmission. • Power Activation and Switching Module Developed by Lockheed Martin, the Boeing Company, and JPL The module was a "smart" power switch consisting of eight power switches grouped in redundant pairs; it could monitor four electrical loads. The switches sensed voltage and current and could limit current if necessary. Secondary Payload • The SEDSAT, an amateur radio satellite conducting remote sensing. The SEDSAT detached from the rocket about 90 minutes later to begin orbiting Earth.
Results	Deep Space 1 successfully tested 12 new technologies for future space use.
Remarks	• First use of ion propulsion as primary propulsion source. • First use of autonomous navigation in deep space. • First New Millennium Program technology validation mission.

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[a] "Testing Technologies," *http://nmp.jpl.nasa.gov/ds1/gen/gen2.html* (accessed August 11, 2005). Also "Plasma Experiment for Planetary Exploration (PEPE)," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1998-061A&ex=2* (accessed August 18, 2005). Also "Deep Space 1 Launch Press Kit," October 1998 (NASA History Office Electronic File 30203).

Table 4–56. High Energy Transient Experiment, Satelite de Aplicaciones Cientificas-B Dual Mission Characteristics

Launch Date/Launch Site	November 4, 1996 / Wallops Island, Virginia
Date of Reentry	April 2, 2002
Launch Vehicle	Pegasus XL
NASA Role	HETE: Collaboration between NASA and MIT. Managed by NASA as a University Explorer mission of opportunity. SAC-B: Provided one scientific instrument, launch services, support for initial orbit operations and emergency backup through mission life.
Responsible (Lead) Center	Goddard Space Flight Center (Wallops Flight Facility)
Mission Objectives	HETE: To carry out the first multiwavelength study of gamma-ray bursts with UV, x-ray, and gamma-ray instruments. SAC-B: To study solar physics and astrophysics through the examination of solar flares, gamma-ray burst sources, and the diffuse soft x-ray cosmic background.
Orbit Characteristics	Did not reach orbit
Weight	SAC-B: 181 kg (399 lb) HETE: 128 kg (282 lb)
Dimensions	SAC-B: Body: 62 cm by 62 cm (2 ft by 2 ft) wide by 80 cm (2.6 ft) high; four solar panels 62 cm (2 ft) wide by 76 cm (2.5 ft) long when extended HETE: Body fit within a cylinder 89-cm high by 66-cm diameter
Power Source	Solar arrays and batteries
Prime Contractor	HETE: AeroAstro, L.L.C. SAC-B: INVAP S.W.
Instruments and Experiments	SAC-B: • Hard X-Ray Spectrometer (HXRS) Instrument Manager: Ana Maria Hernandez, Argentinean National Commission of Space Activities The instrument was provided by the Argentine Institute of Astronomy and Space Physics. The instrument was to search the hard x-ray spectrum between 20 keV and 320 keV for rapidly varying events on timescales as short as tens of milliseconds.

Table 4–56. High Energy Transient Experiment, Satelite de Aplicaciones Cientificas-B Dual Mission Characteristics

Instruments and Experiments	• Goddard X-Ray Experiment (GXRE) PI: Brian Dennis, Goddard Space Flight Center The instrument had two detectors: the Soft X-Ray Spectrometer (SOXS) was to perform coordinated observations with the HXRS by observing soft x-ray emissions from solar flares. The Gamma Ray Burst Spectrometer (GRaBS) was to provide time profiles of the x-ray emission from non-solar gamma-ray bursts in the energy range from ~20 keV to >300 keV. • Cosmic Unresolved X-Ray Background Instrument Using CCDs (CUBIC) PI: Gordon Garmire, Pennsylvania State University The instrument was to measure the spectrum of the diffuse x-ray background with unprecedented sensitivity and spectral resolution between 0.1 keV and 10.0 keV in selected areas of the sky. • Imaging Particle Spectrometer for Energetic Neutral Atoms (ISENA) PI: Stefano Orsini, Franscati, Italy Provided by the Italian Istituto di Fisica dello Spazio Interplanetario (Institute for Interplanetary Space Physics), the ISENA was to measure neutral atoms at spacecraft altitudes HETE: • French Gamma Telescope (FREGATE) PI: Gilbert Vedrenne, Centre d'Etude Spatiale des Rayonnements (CESR), France The FREGATE consisted of four wide-field gamma-ray detectors, supplied by the CESR of Toulouse, France, to handle the detection and spectroscopy of gamma-ray bursts and monitor variable x-ray sources. • Wide-Field X-ray Monitor (WXM) PI: Masuaru Majsuoka, RIKEN, Japan The WXM was supplied by a collaboration of the Los Alamos National Laboratory and the Institute of Chemistry and Physics (RIKEN) of Tokyo, Japan. The WXM was the prime instrument for detecting x-ray sources. • Ultraviolet CCD cameras (4) PI: George Ricker, Massachusetts Institute of Technology The cameras were built by MIT's Center for Space Research; three cameras were identical; one had an optical filter. The cameras were to provide the most accurate directional information about transient events and assist with spacecraft attitude determination.
Results	Failed to reach orbit.

Table 4–57. Geotail Mission Characteristics

Launch Date/Launch Site	July 24, 1992/Cape Canaveral Air Force Station
Date of Reentry	Still operating in mid-2005.[a]
Launch Vehicle	Delta II
NASA Role	Project management, two scientific instruments, two other scientific instruments jointly with the ISAS, launch vehicle and launch support
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Acquire in situ data defining the field and particle environments of the geomagnetic tail region of the magnetosphere. Science objectives: • Determine the overall plasma electric and magnetic field characteristics of the distant and near geomagnetic tail. • Help determine the role of the distant and near-Earth tail in substorm phenomena and in the overall magnetospheric energy balance. Also relate these phenomena to external triggering mechanisms. • Study the processes that initiate reconnection in the near-Earth tail and observe the microscopic nature of the energy conversion mechanism in this reconnection region. • Determine the composition and charge state of plasma in the geomagnetic tail at various energies during quiet and dynamic periods and distinguish between the ionosphere and solar wind as sources of this plasma. • Study plasma entry, energization, and transport processes in interaction regions such as the inner edge of the plasma sheet, the magnetopause, and the bow shock, and investigate boundary layer regions.
Orbit Characteristics	Two orbits: approximately 220 Earth radii (1,401,620 km) and 8 Earth radii (51,024 km) by 30 Earth radii (191,340 km)
Weight	1,009 kg (2,220 lb) including 360 kg (792 lb) of hydrazine fuel
Dimensions	Diameter: 2.2 m (7.2 ft); height: 1.6 m (5.2 ft)
Shape	Cylindrical
Power Source	Body-mounted solar cell panel, nickel cadmium batteries
Prime Contractor	Institute of Space and Astronautical Science, Japan

Table 4–57. Geotail Mission Characteristics (Continued)

Instruments and Experiments	• Comprehensive Plasma Investigation (CPI) PI: Louis A. Frank, University of Iowa The CPI made comprehensive observations of the three-dimensional velocity distribution functions of electrons and positive ions, with identification of ion species. The instrument contained three sets of quadrispherical analyzers with channel electron multipliers that obtained three-dimensional measurements for hot plasma and solar wind electrons, solar wind ions, and positive-ion composition measurements. • Energetic Particle and Ion Composition (EPIC) Investigation PI: Richard McEntire, The Johns Hopkins University Applied Physics Laboratory The EPIC investigation explored the distant magnetotail region and obtained information on the origin, transport, storage, acceleration, and dynamics of suprathermal and nonthermal particle populations. The investigation was composed of two separate sensor and processing assemblies. The Supra-Thermal Ion Composition Spectrometer assembly measured charge state, mass, and energy of ions with energies from 30 keV to 230 keV per charge. The Ion Composition Subsystem assembly measured mass and energy properties of energetic ions with energies of less than 50 keV to 3 MeV. • Plasma Wave Investigation (PWI) PI: Hiroshi Matsumoto, Radio Atmospheric Science Center, Kyoto University This investigation determined the dynamic behavior of the plasma trapped in Earth's magnetosphere by measuring electric fields over the range from 0.5 Hz to 400 kHz and magnetic fields over the range from 1 Hz to 10 kHz. Triaxial magnetic search coils were used in addition to a pair of electric dipole antennae. The instrument contained two sweep-frequency receivers (12 Hz to 400 kHz and 12 Hz to 6.25 kHz), a multichannel analyzer (5.6 Hz to 311 kHz for the electric antenna and 5.6 Hz to 1.0 kHz for the magnetic coils), a low-frequency waveform receiver (0.01 Hz to 10 Hz), and a wideband waveform receiver (10 Hz to 16 kHz).

Table 4–57. Geotail Mission Characteristics (Continued)

Instruments and Experiments	• Electric Fields Detector (EFD) Investigation PI: Koichiro Tsuruda, Institute of Space and Astronautical Science, Japan The EFD investigated: — The large-scale configuration of the electric field in the magnetotail. — Magnetotail electric field variations during substorms. — The electric field in the plasma sheet. — The electric field near the magnetopause and in the plasma mantle at locations tailward of those covered by similar measurements on the International Sun Earth Explorer (ISEE) 1. — Micropulsation and low-frequency wave measurements at frequencies covering the local gyrofrequency (<1 Hz) and lower hybrid frequency (<10 Hz) in the magnetotail. — Plasma density as deduced from measurement of the floating potential of the spacecraft. — Electric field comparisons (with the aid of the other spacecraft in the ISTP program) at different points along the same magnetic field line, at different points along a common boundary, or in different regions of the magnetosphere. • The instrument consisted of two orthogonal double probes, each a pair of separated spheres on wire booms located in the satellite spin plane. The difference of potential between the spheres was measured. • High-Energy Particles (HEP) Investigation PI: Tadayoshi Doke, Waseda University, Japan The HEP investigation studied the following: 1) plasma dynamics in the geomagnetic tail, 2) solar flare particle acceleration and propagation, and 3) the origin, lifetime, and propagation of cosmic ray particles. Five instruments made up this investigation: a low-energy particle detector (LD), a burst detector (BD), medium-energy isotope detectors (MI-1 and MI-2), and a high energy Isotope detector (HI). LD and BD were mainly dedicated to magnetospheric studies. MI and HI concentrated on solar flare and cosmic-ray studies. • Low-Energy Particles (LEP) Experiment PI: Toshifumi Mukai, Institute of Space and Astronautical Science, Japan

Table 4–57. Geotail Mission Characteristics (Continued)

Instruments and Experiments[b]	The LEP experiment observed plasma and energetic electrons and ions in the terrestrial magnetosphere and interplanetary medium. The experiment consisted of three sensors sharing common electronics. LEP-electrostatic analyzers (EA) measured three-dimensional velocity distributions of hot plasma in the magnetosphere. The LEP-solar wind measured three-dimensional velocity distributions of solar wind ions in the energy range from 0.1 keV/Q to 8 keV/Q. The LEP-mass spectrometer was an energetic ion mass spectrometer that provided three-dimensional determinations of the ion composition in 32 steps in the energy range from 0 keV/Q to 25 keV/Q. All sensors operated continuously as long as spacecraft power allowed except during the orbit/attitude maneuvering operation. Although this experiment ceased operation soon after launch, the LEP-EA and LEP-SW portions of the experiment resumed operation in late 1993 and have worked ever since. • Magnetic Fields Measurement (MGF) PI: Tsugunobu Nagai, Tokyo Institute of Technology, Earth and Planetary Sciences, Japan This experiment measured the magnetic field variation of the magnetotail in the frequency below 50 Hz. The experiment consisted of dual three-axis fluxgate magnetometers and a three-axis search coil magnetometer. Triad fluxgate sensors were installed at the end and middle of a 6-m (20-ft) deployable mast. Three search coils were mounted approximately one-half of the way out on another 6-m (20-ft) boom.
Results[c]	In the area of magnetotail structure, dynamics, and plasma population, Geotail observations demonstrated that the structure and dynamics of the magnetotail were basically determined by magnetic reconnection under both southward and northward interplanetary magnetic field (IMF) conditions, except possibly when IMF was almost due northward. Relating to the role of magnetic reconnection in the magnetospheric substorm, Geotail observations significantly advanced our understanding of magnetic reconnection in the near-Earth tail for the magnetospheric substorm. Relating to characteristic plasma waves in the magnetotail, Geotail made a thorough survey of plasma waves in the magnetotail and clarified its relation to the macroscopic structure.

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[a] "Geotail," *http://directory.eoportal.org/pres_GEOTAIL.html* (accessed September 2, 2005).

[b] "Geotail, Instrument Descriptions," *http://www-spof.gsfc.nasa.gov/istp/geotail/geotail_inst.html* (accessed September 2, 2005).

[c] "Typical Important Results," Institute of Space and Astronautical Science, *http://www.isas.jaxa.jp/e/enterp/missions/geotail/achiev/typical.shtml* (accessed September 2, 2005).

Table 4–58. Wind Mission Characteristics

Launch Date/Launch Site	November 1, 1994 / Cape Canaveral Air Station
Date of Reentry	None
Launch Vehicle	Delta II 7925
NASA Role	Project management, PIs for four U.S. instrument and Russian KONUS instrument
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Science objectives (Wind Project Overview)[a] • Provide complete plasma, energetic particle, and magnetic field input for magnetospheric and ionospheric studies. • Determine the magnetospheric output to interplanetary space in the up-stream region. • Investigate basic plasma processes occurring in the near-Earth solar wind. • Provide baseline ecliptic plane observations to be used in heliospheric latitudes from Ulysses. Science objectives (Mission Operation Report)[b] • Measure the mass, momentum, and energy flows through geospace and understand their time variability. • Obtain detailed knowledge of plasma physical processes important in controlling the behavior of the major components of the geospace system. • Determine the importance of changes in energy input to Earth's atmosphere caused by geospace processes.
Orbit Characteristics	Two orbits: apogee from 80 Earth radii to 250 Earth radii and perigee between 5 Earth radii and 10 Earth radii (31,890 km and 63,780 km) followed by a halo orbit about the sunward Sun-Earth gravitational equilibrium point (L1) varying from 235 Earth radii to 265 Earth radii (864,330 km to 1,690,170 km).
Weight	Launch weight: 1,250 kg (2,756 lb), spacecraft weight: 884 kg (1,949 lb)
Dimensions	Diameter: 2.4 m (7.87 ft), height: 1.8 m (5.91 ft)[c]
Shape	Cylindrical
Power Source	Solar panels and battery
Prime Contractor	Spacecraft: Martin Marietta[d]

Table 4–58. Wind Mission Characteristics (Continued)

Instruments and Experiments	• Radio and Plasma Wave Experiment (WAVES) PI: J.L. Bougeret, Laboratoire de Recherche Spatiale, France The WAVES measured the intensity and arrival direction for both propagating and *in situ* waves originating in the solar wind near Earth. These waves depict the state of the solar wind impinging on Earth's magnetosphere. The instrument contained five subsystems within the main electronics box, plus the antenna subsystems that included a spin-axis and two spin-plane electric antennae and a triaxial search coil. The WAVES had on-board interconnects with the 3-D Plasma investigation (3D PLASMA) and the Solar Wind Experiment (SWE). • Energetic Particle Acceleration, Composition and Transport (EPACT) PI: T. von Rosenvinge, Goddard Space Flight Center The EPACT instrument provided a comprehensive study of energetic particle acceleration and transport processes in solar flares, the interplanetary medium, and planetary magnetospheres, as well as the galactic cosmic rays and the anomalous cosmic ray component. The instrument consisted of three integrated telescope/electronics boxes mounted on the body of the spacecraft. The extensive dynamic range of particles to be measured was divided among three Low Energy Matrix Telescopes (LEMTs), two Alpha-Proton-Electron (APE) telescopes, an Isotope Telescope (IT), and a Supra Thermal Energetic Particle (STEP) telescope. An on-board recorder allowed continuous observations to be made. • SWE PI: K. Ogilvie, Goddard Space Flight Center The SWE provided complete, accurate specification of solar wind flow parameters in real time. The instrument was a six-axis ion-electron spectrometer that provided three-dimensional velocity distribution functions for ions and electrons, with high time resolution.

Table 4–58. Wind Mission Characteristics (Continued)

Instruments and Experiments	• Solar Wind and Suprathermal Ion Composition Experiment (SMS) PI: G. Gloeckler, Institute of Physical Sciences and Technology, University of Maryland This experiment consisted of three major instruments: 1) the SWICS, 2) the High Mass Resolution Spectrometer (MASS), and 3) the Suprathermal Ion Composition Spectrometer (STICS). This experiment determined the abundance, composition, and differential energy spectra of solar wind ions, as well as the composition, charge state and three-dimensional distribution functions of suprathermal ions. These ions, and their abundance fluctuations, provided information about events on the solar surface and the formation of the solar wind, complementing the EPACT and 3D PLASMA investigations. • Magnetic Field Investigation (MFI) PI: R. Lepping, Goddard Space Flight Center The MFI investigated the large-scale structure and fluctuation characteristics of the interplanetary magnetic field, which influenced the transport of energy and the acceleration of particles in the solar wind and dynamic processes in Earth's magnetosphere. The MFI consisted of dual triaxial fluxgate magnetometers mounted on a 12-m (40-ft) radial boom and a data processing and control unit within the spacecraft body. Mounting the magnetometers at the outboard end and at an inboard location on the boom helped reduce contamination of the measurements by spacecraft-generated magnetic fields. • 3D PLASMA PI: R. Lin, Space Sciences Laboratory, University of California, Berkeley The 3D PLASMA investigation measured ions and electrons in the interplanetary medium with energies including that of the solar wind and the energetic particle range. The experiment studied the particles upstream of the bow shock in the foreshock region and the transient particles emitted by the Sun during solar particle events following solar flares. This experiment covered the gap between the energy ranges covered by the SWE and EPACT.

Table 4–58. Wind Mission Characteristics (Continued)

Instruments and Experiments	The 3D PLASMA investigation consisted of two sensor packages mounted on small radial booms and an electronics package mounted inside the spacecraft. One boom-mounted sensor package contained an array of six double-ended semiconductor telescopes, each with two or three closely sandwiched silicon detectors to measure electrons and ions above 20 keV. The first sensor package also contained two ion electrostatic analyzers for measuring ion fluxes from approximately 3 keV to 40 keV. The second sensor package contained two electron electrostatic analyzers for measuring electron fluxes from about 3 keV to 30 keV and for making input to a fast particle correlator (FPC). The FPC, using plasma wave data from the WAVES, measured perturbations to the electron distribution function and studied other wave-particle interactions. • Transient Gamma Ray Spectrometer (TGRS) PI: B.J. Teegarden, Goddard Space Flight Center The TGRS detected several gamma-ray bursts and solar flares per week, with typical durations between 1 second and several minutes. Between bursts, the instrument remained in a waiting mode, measuring background counting rates and energy spectra. When a burst or flare occurred, the instrument switched to a burst mode, where each event in the detector was pulse-height analyzed and time tagged in a burst memory. Then the instrument switched to a dump mode for reading out the burst memory. The TGRS consisted of four assemblies: detector cooler assembly, pre-amp, analog processing unit (all mounted on a tower on the +Z end of the spacecraft), and a digital processing unit mounted in the body of the spacecraft.
Instruments and Experiments[e]	• Russian Gamma-Ray Spectrometer (KONUS) PIs: T.L. Cline, Goddard Space Flight Center; E. Mazets, IOFFE Physical Technical Institute, Russia The KONUS performed gamma-ray burst studies similar to the TGRS studies. It performed event detection and measured time history and energy spectra. Although KONUS had a lower resolution than the TGRS, the spectrometer had broader area coverage to complement that of the TGRS; the combined KONUS and TGRS data provided coverage of the full sky. The KONUS was the first Russian experiment on a NASA science mission. The KONUS consisted of two Russian sensors mounted on the top and bottom of the spacecraft aligned with the spin axis, a U.S. interface box, and a Russian electronics package mounted in the spacecraft body. The sensors (copies of sensors successfully flown on the Soviet Cosmos, Venera, and *Mir* missions) were identical and interchangeable.

Table 4–58. Wind Mission Characteristics (Continued)

Results	In addition to being an essential part of the ISTP program, Wind provided new results in heliospheric science and astrophysics, and it provided further investigations of the Sun-Earth connection.[f]

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[a] "Wind Project Overview," *http://pwg.gsfc.nasa.gov/istp/wind/wind.html* (accessed September 2, 2005).

[b] Wind Mission Operations Report," Report no. S-417-94-01 (NASA History Office Folder 30999 Electronic Document).

[c] Finneran, "Wind Spacecraft Scheduled To Launch Nov. 1 at the Cape," *Goddard News* 41 (October 1994): 1–2. (NASA History Office Folder 5910). This figure is very close to the figures cited in the Wind Mission Operations Report. The NSSDC database master catalog *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1994-071A* (accessed July 18, 2006) states the diameter as 2.8 m and height as 1.25 m.

[d] Jim Elliot, "Launches of Wind and STS-66 Successful," *Goddard News* 41 (November 1994): 1 (NASA History Office Folder 5910).

[e] "Wind Instrument Descriptions," *http://pwg.gsfc.nasa.gov/wind_inst.shtml* (accessed May 16, 2006).

[f] K.W. Ogilvie and M.D. Desch, "The WIND Spacecraft and Its Early Scientific Results," *http://www-ssc.igpp.ucla.edu/IASTP/04* (accessed October 25, 2005).

Table 4–59. Polar Mission Characteristics

Launch Date/Launch Site	February 24, 1996 / Vandenberg Air Force Base
Date of Reentry	Operational as of mid-2005.
Launch Vehicle	Delta II
NASA Role	Program management and operation of the spacecraft; PI for TIDE/PSI
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	• Determine the role of the ionosphere in the substorm phenomena and in the overall magnetospheric energy balance. • Measure plasma energy input through the dayside cusp. • Determine the characteristics of ionospheric plasma outflow and energized plasma inflow to the atmosphere. • Study characteristics of the auroral plasma acceleration regions. • Provide multispectral auroral images of the footprint of the magnetospheric energy deposition into the ionosphere and upper atmosphere.
Orbit Characteristics:	
Apogee	51,000 km (31,690 mi)
Perigee	5,100 km (3,169 mi)
Inclination (deg)	86
Period (min)	1,050
Weight	Total weight: 2,860 lb (1,300 kg); fuel weight: 662 lb (301 kg); dry weight: 2,198 lb (999 kg)
Dimensions[a]	Height: 2.28 m (7.5 ft) (including despun platform); diameter: 2.49 m (8.2 ft)
Shape	Cylindrical
Power Source	Solar array, three batteries
Prime Contractor	Lockheed Martin Corp.
Instruments and Experiments	• Magnetic Fields Experiment (MFE) PI: Christopher T. Russell, University of California, Los Angeles The MFE was a high-precision instrument designed to measure the magnetic fields in the high and low altitude polar magnetosphere. The MFE was used to investigate the behavior of field-aligned current systems and the role they played in the acceleration of particles and dynamics of the fields in the polar cusp, magnetosphere, and magnetosheath.

Table 4–59. Polar Mission Characteristics (Continued)

Instruments and Experiments	• Electric Fields Instrument (EFI) PI: Forrest S. Mozer, Space Sciences Laboratory, University of California, Berkeley The EFI measured the three components of the ambient vector electric field and the thermal electron density. The results were used to study the following: — Parallel and perpendicular electric fields and density variations in double layers, electrostatic shocks, and other time domain structures found in the auroral acceleration region and at other locations in the Polar orbit. — The high latitude convection electric field. — The electric field and plasma density structure on field lines connected to the high-latitude magnetopause, polar cusp, and plasma mantle. — Correlations of electric fields with those measured by other ISTP program spacecraft at different points along the same magnetic field line or along a common boundary, or in different regions of the magnetosphere. — Modes, phase velocities, and wavelengths of propagating waves and spatial structures. • Plasma Waves Investigation (PWI) PI: Donald A. Gurnett, University of Iowa The PWI provided comprehensive measurements of plasma wave phenomena in the high-latitude auroral zones, dayside magnetic cusp regions, and plasmasphere and plasma sheet. The investigation used seven distinct sensors to detect the electric and magnetic fields of plasma waves. • Hot Plasma Analyzer (HYDRA) PI: Jack D. Scudder, University of Iowa The HYDRA consisted of a collection of electrostatic analyzers designed for high-resolution observations of electron and ion velocity distributions in Earth's polar magnetosphere. The scientific objectives were the following: — To observe the velocity space signatures identifying the sources of particles detected in the polar magnetosphere. — To improve understanding of the coupling of the plasma to the magnetic field in the polar magnetosphere where ideal magnetohydrodynamics ordering breaks down. — To elucidate time-dependent processes occurring in the auroral zone.[b]

Table 4–59. Polar Mission Characteristics (Continued)

Instruments and Experiments[c]	• Thermal Ion Dynamics Experiment (TIDE)/Plasma Source Instrument (PSI) PI: Thomas E. Moore, Goddard Space Flight Center This experiment and instrument were developed to meet the requirements for three-dimensional plasma composition measurements capable of tracking the outflow of ionospheric plasma throughout the magnetosphere. • Toroidal Imaging Mass Angle Spectrograph (TIMAS): PI: William K. Peterson, Space Physics Laboratory, Lockheed Martin Advanced Technology Center The TIMAS measured the full three-dimensional velocity distribution functions of all major magnetospheric ion species with one-half spin period time resolution. • Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE) PI: Theodore A. Fritz, Center for Space Physics, Boston University The CAMMICE's objective was to determine unambiguously the composition of the energetic particle populations of Earth's magnetosphere in the range from 6 keV/Q to 60 MeV per ion to identify mechanisms by which these charged particles were energized and transported from their parent source populations to the magnetosphere. • CEPPAD/SEPS PI: J. Bernard Blake, Space Sciences Department, The Aerospace Corporation Consisted of three packages: two were spacecraft body-mounted and the third was located on the despun platform. The first body-mounted package consisted of the Imaging Proton Sensor (IPS) and the Digital Processing Unit (DPU). The second consisted of the Imaging Electron Sensor (IES) and the High Sensitivity Telescope. The single despun platform package was the SEPS. • UVI PI: George K. Parks, University of Washington The UVI was a two-dimensional imager sensitive to far UV wavelengths. With its 8-degree circular FOV, the UVI imaged the sunlit and nightside polar regions of Earth in the far UV wavelengths. The UVI detected and provided images of very dim emissions with a wavelength resolution never achievable before. The resulting images helped quantify the overall effects of solar energy input to Earth's polar regions.

Table 4–59. Polar Mission Characteristics (Continued)

Instruments and Experiments	• VIS PI: L.A. Frank, University of Iowa The VIS was a set of three low-light-level cameras. Two cameras shared primary and some secondary optics, and they were designed to provide images of the nighttime auroral oval at altitudes from about 1 Earth radii to 8 Earth radii (6,378 km to 51,024 km) as viewed from the eccentric, polar orbit of the spacecraft. A third camera monitored the directions of the FOVs of the auroral cameras with respect to the sunlit Earth. • PIXIE PI: David L. Chenette, Space Physics Laboratory, Lockheed Martin Advanced Technology Center The PIXIE measured the spatial distribution and temporal variation of x-ray emissions in the energy range from 3 keV to 60 keV from Earth's atmosphere. The morphology and spectra of energetic electron precipitation and its effects upon the atmosphere were derived from these x-ray measurements.
Results	This was a successful mission performing multi-wavelength imaging of the aurora, measuring the entry of plasma into the polar magnetosphere and the geomagnetic tail, the flow of plasma to and from the ionosphere, and the deposition of particle energy in the ionosphere and upper atmosphere.

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[a] John B. Sigwarth, Polar Project Scientist, e-mail, August 11, 2005.

[b] "HYDRA Instrument Page," *http://www-st.physics.uiowa.edu/www/html/instrument.html* (accessed October 25, 2005).

[c] "Polar Instrument Descriptions," *http://www-spof.gsfc.nasa.gov/istp/polar/polar_inst.html* (accessed August 10, 2005).

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics

Launch Date/Launch Site	December 2, 1995/Cape Canaveral Air Station
Date of Reentry	Still in orbit as of mid-2005.
Launch Vehicle	Atlas IIAS
NASA Role	Launch vehicle; instrument interface hardware; mission and science operations; DSN support; data processing and archive
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To study and understand the solar corona—in particular, its heating mechanism and its expansion into the solar wind—both by remote sensing of the solar atmosphere with high-resolution spectrometers and by *in situ* measurements of the composition of the resulting particles in the solar wind. • To study the solar structure and interior dynamics from the Sun's core to the photosphere by helioseismological methods and the measurement of the solar irradiance variations.
Orbit Characteristics	Orbits around first Lagrangian point (L1) approximately 1.5 million km (1 million mi) from Earth in the direction of the Sun. Circles the L1 point once every six months.
Weight	1,850 kg (4,079 lb) at launch
Dimensions	4.3 m by 2.7 m by 3.7 m (14.1 ft by 8.9 ft by 12.1 ft); 9.5 m (31.2 ft) with solar arrays deployed
Power Source	Solar array and batteries
Prime Contractor	Matra Marconi under contract to the ESA
Instruments and Experiments	Solar Corona • Coronal Diagnostic Spectrometer (CDS) PI: Richard Harrison, Rutherford Appleton Laboratory, U.K. The CDS detected emission lines from ions and atoms in the solar corona and transition region, providing diagnostic information on the solar atmosphere, especially of the plasma in the temperature range from 10,000°C (18,032°F) to more than 1,000,000°C (1,800,032°F).

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics (Continued)

Instruments and Experiments	• Large Angle and Spectrometric Coronograph (LASCO) PI: Guenter Brueckner, Naval Research Laboratory The LASCO observed the outer solar atmosphere (corona) from near the solar limb to a distance of 21 million km (13 million mi), that is, about one-seventh of the distance between the Sun and Earth. The LASCO blocked direct light from the surface of the Sun with an occulter, creating an artificial eclipse, 24 hours a day, seven days a week. The LASCO became the SOHO's principal comet finder. • Solar Wind Anisotropies (SWAN) PI: Jean Loup Bertaux, National Center for Scientific Research (CNRS), Verrièrres-Le-Buisson, France The SWAN was the SOHO's only remote sensing instrument that did not look at the Sun. The SWAN watched the rest of the sky, measuring hydrogen "blowing" into the solar system from interstellar space. By studying the interaction between the solar wind and this hydrogen, the SWAN determined how the solar wind was distributed. The SWAN could be characterized as the SOHO's solar wind "mapper." • Ultraviolet Coronograph Spectrometer (UVCS) PI: John Kohl, Smithsonian Astrophysical Observatory, Cambridge, MA The UVCS made measurements in UV light of the solar corona (between about 1.3 solar radii and 12 solar radii from the center) by creating an artificial solar eclipse. The spectrometer blocked the bright light from the solar disc and allowed observation of the less intense emission from the extended corona. The UVCS provided valuable information about the microscopic and macroscopic behavior of the highly ionized coronal plasma. • Solar Ultraviolet Measurements of Emitted Radiation (SUMER) PI: Klaus Wilhelm, Max Planck Institute, Germany This instrument performed detailed spectroscopic plasma diagnostics (flows, temperature, density, and dynamics) of the solar atmosphere, from the chromosphere through the transition region to the inner corona, over a temperature range from 10,000°C (18,032°F) to 2,000,000°C (3,600,032°F) and above.

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics (Continued)

Instruments and Experiments	• Extreme Ultraviolet Imaging Telescope (EIT) PI: Jean Pierre Delaboudinière, Laboratory for Stellar and Planetary Physics, Orsay, France The EIT provided full disc images of the Sun at four selected colors in the EUV, mapping the plasma in the low corona and transition region at temperatures between 80,000°C (144,034°F) and 2,500,000°C (4,500,032°F). Solar Wind • Charge, Element, and Isotope Analysis System (CELIAS) PI: Dietrich Hovestadt, Max Planck Institute, Germany The CELIAS continuously sampled the solar wind and energetic ions of solar, interplanetary, and interstellar origin as they swept past the SOHO. The CELIAS analyzed the density and composition of particles present in this solar wind and warned of incoming solar storms that could damage satellites in Earth orbit. • Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) PI: Horst Kunow, University of Kiel, Germany The COSTEP detected and classified very energetic particle populations of solar, interplanetary, and galactic origin. It was a complementary instrument to the Energetic and Relativistic Nuclei and Electron (ERNE) experiment. • ERNE experiment PI: Jarmo Torsti, University of Turku, Finland The ERNE experiment measured high-energy particles originating from the Sun and Milky Way. The ERNE experiment was a complementary instrument to the COSTEP. Solar Interior • Global Oscillations at Low Frequencies (GOLF) PI: Alan Gabriel, Laboratory for Stellar and Planetary Physics, France This instrument measured velocity oscillations over the entire solar disc to study the internal structure of the Sun.

Table 4–60. Solar and Heliospheric Observatory Mission Characteristics (Continued)

Instruments and Experiments[b]	• Michelson Doppler Imager/Solar Oscillations Investigation (MDI/SOI) PI: Philip Scherrer, Stanford University The MDI/SOI recorded the vertical motion ("tides") of the Sun's surface at a million different points for each minute. By measuring the acoustic waves inside the Sun as they perturbed the photosphere, scientists could study the structure and dynamics of the Sun's interior. The MDI also measured the longitudinal component of the Sun's magnetic field. • Variability of Solar Irradiance and Gravity Oscillations (VIRGO) PI: Claus Fröhlich, Physical-Meteorological Observatory, Davos, Switzerland This instrument characterized solar intensity oscillations and measured the total solar irradiance (known as the "solar constant") to quantify its variability spanning periods of days to the duration of the mission.
Results	The SOHO revolutionized solar science by its special ability to observe simultaneously the interior and atmosphere of the Sun and particles in the solar wind and heliosphere. The SOHO made remarkable discoveries about flows of gas inside the Sun, giant "tornadoes" of hot, electrically charged gas, and clashing magnetic field-lines. The observatory also gave early warnings of solar eruptions that could affect Earth.
Remarks	Extending the mission past its April 1998 prime mission enabled the SOHO to observe intense solar activity in 2000 and compare the activity to the Sun's behavior during low dark sunspot activity in 1996.

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[a] "Solar and Heliospheric Observatory (SOHO): International Solar Terrestrial Physics Program," *1995 Flight Project Data Book*, p. 82 (NASA History Office Folder 14567).

[b] "SOHO," Factsheet, ESA Media Centre, Space Science, June 1, 2003, *http://www.esa.int/esaSC/SEMJFH374OD_0_spk.html* (accessed August 8, 2005). Also "Solar and Heliospheric Observatory (SOHO)," NASA and ESA (NASA History Office Folder 14567).

Table 4–61. Solar-A/Yohkoh Mission Characteristics

Launch Date/Launch Site	August 30, 1991 / Kagoshima Space Center, Japan
Date of Reentry	Mission ended in December 2001 after a spacecraft failure.
Launch Vehicle	M-3S2
NASA Role	Managed SXT development; provided tracking support using DSN ground stations
Responsible (Lead) Center	Marshall Space Flight Center
Mission Objectives	To study the high-energy radiations from solar flares (hard and soft x-rays and energetic neutrons), as well as study quiet structures and pre-flare conditions. NASA objectives: • To obtain simultaneous images of solar flares with high time and spatial resolutions in both the hard and soft x-rays so that the full morphology of the flare can be observed with sufficient precision to reveal the underlying physical processes. • To image the solar corona in soft x-rays, with both high time and spatial resolution, to reveal properties of the global coronal magnetic fields. • To measure variations of photospheric brightness with modest spatial resolution for studies of solar irradiance and global oscillations.
Orbit Characteristics:	
Apogee	Initial orbit: 792.6 km (492.5 mi)
Perigee	Initial orbit: 517.9 km (321.8 mi)
Inclination (deg)	31
Period (min)	90
Weight	420 kg (926 lb)
Dimensions	4 m by 4 m by 2 m (13.1 ft by 13.1 ft by 6.6 ft)
Shape	Rectangular
Power Source	Solar panels and batteries
Prime Contractor	Lockheed Martin

Table 4–61. Solar-A/Yohkoh Mission Characteristics (Continued)

Instruments and Experiments	• SXT PI: Tadashi Hirayama, National Astronomical Observatory of Japan The SXT formed x-ray images in the range from 0.25-keV to 4.0-keV on a 1024-pixel by 1024-pixel CCD using grazing-incidence optics. It used thin metallic filters to acquire images in restricted portions of this energy range. The SXT could resolve features down to 2.5 arc seconds in size. Information about the temperature and density of the plasma emitting the observed x-rays was obtained by comparing images acquired with the different filters. Flare images could be obtained every 2 seconds. Smaller images with a single filter could be obtained as frequently as once every 0.5 second. This instrument was made of two highly polished cylindrical surfaces ground to high-precision hyperbolas. X-rays entered the front of the mirror cylinders nearly parallel to the mirror surfaces. They grazed off the two surfaces to the focal point where an x-ray detector was located. The x-ray pictures were sent to the ground where scientists analyzed the data.[a] • HXT PI: Kazuo Makishima, University of Tokyo The HXT was a multigrid synthesis-type imager with a spatial resolution of 7 arc seconds, operating in the range from 20-keV to 80-keV. It observed hard x-rays in four energy bands through 64 pairs of grids. These grid pairs provided information about 32 spatial scales of the x-ray emission. This information was combined on the ground to construct an image of the source in each of the four energy bands. Structures with angular sizes down to about 5 arc seconds could be resolved. The instrument could obtain images as frequently as once every 0.5 seconds. • BCS PI: George A. Doschek, Naval Research Laboratory The BCS consisted of four bent crystal spectrometers. Each was designed to observe a limited range of soft x-ray wavelengths containing spectral lines sensitive to the hot plasma produced during a solar flare. The observations of these spectral lines provided information about the temperature and density of the hot plasma and about motions of the plasma along the line of sight. Images were not obtained, but this was offset by enhanced sensitivity to the line emission, high spectral resolution, and time resolution on the order of 1 second.

Table 4–61. Solar-A/Yohkoh Mission Characteristics (Continued)

Instruments and Experiments	• WBS PI: Jun Nishimura, Institute of Space and Astronomical Science, Japan The WBS consisted of three subinstruments that together spanned the entire energy range from soft x-rays to gamma rays, 2 keV to 100 MeV, with a time resolution on the order of 1 second or better. The detectors were: 1) the soft x-ray spectrometer, a gas proportional counter filled with xenon and carbon dioxide that covered the 2-keV to 30-keV band; 2) the hard x-ray spectrometer, a NaI scintillator covering the energy range from 20-keV to 600-keV; and 3) the gamma-ray spectrometer, a pair of identical BGO scintillators ($Bi_4 Ge_3 O_{12}$) (bismuth germinate) covering the 0.2-MeV to 100-MeV band.[b] Images were not obtained.
Results[c]	Yohkoh made discoveries about: • The Sun's corona, including information about how and where this outer layer of the Sun's atmosphere was heated to temperatures up to hundreds of times greater than the solar surface. Yohkoh also tracked the dramatic year-to-year evolution of the corona. • The physics of solar flares, titanic explosions in the atmosphere of the Sun caused by the violent release of magnetic energy. In less than 1 hour, a typical solar flare can release as much as 10,000 times the annual energy consumption of the United States. Yohkoh observations helped astronomers understand how the Sun's magnetic fields were deformed and twisted; broken and reconnected during flares; and how the electrified gas (plasma) of the Sun's corona was heated to millions of degrees during flares. • The structures that produce ejections of material from the Sun, helping astronomers understand and begin to predict "space weather." Although the prediction tools were still rudimentary, the discovery that certain structures on the Sun, namely sigmoids and transequatorial interconnecting loops (TIL), were more likely to be the sites of solar eruptions was noteworthy. The sigmoids—S-shaped regions seen in coronal imagery—were found to be more likely to erupt than non-S-shaped regions. The TILs received attention as another possible source of mass ejections.

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[a] "The Yohkoh Satellite," *http://hesperia.gsfc.nasa.gov/sftheory/yohkoh.htm* (accessed August 29, 2005).

[b] "Wide Band Spectrometer," NSSDC Master Catalog: Experiment, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1991-062A&ex=3* (accessed September 25, 2005).

[c] "Yohkoh Mission Celebrates a Decade of Solar Discovery," Goddard Space Flight Center, September 10, 2001, *http://www.gsfc.nasa.gov/topstory/20010917yohkoh.html* (accessed September 22, 2005).

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Table 4–62. NASA Sounding Rocket Launches (1989–1998[a])

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.045 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	January 9, 1989	White Sands Missile Range	Mission unsuccessful, vehicle unsuccessful
36.047 GU	Mentall/ Goddard Space Flight Center	Upper Atmosphere	January 17, 1989	White Sands Missile Range	Successful
AAF-XB-02	Kintner/Cornell University, James/Canadian Research Council	Upper Atmosphere	January 30, 1989	Andoya, Norway	Successful
21.100 GE	Pfaff/ Goddard Space Flight Center	Geospace Sciences	March 3, 1989	Kiruna, Sweden	Successful
21.096 GE	Pfaff/ Goddard Space Flight Center	Geospace Sciences	March 4, 1989	Kiruna, Sweden	Successful
33.057 UL	Barth/University of Colorado	Solar System Exploration	March 7, 1989	Poker Flat Research Range	Successful
31.073 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 18, 1989	Fort Churchill, Canada	Successful
31.074 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 22, 1989	Fort Churchill, Canada	Successful
29.027 UE	Mendillo/Boston University	Geospace Sciences	April 3, 1989	Wallops Island, Virginia	Vehicle successful, mission unsuccessful
35.022 GE	Hoffman/ Goddard Space Flight Center	Geospace Sciences	April 9, 1989	Fort Churchill, Canada	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
350.021 GE	Hoffman/Goddard Space Flight Center	Geospace Sciences	April 11, 1989	Fort Churchill, Canada	Successful
35.019 UE	Torbert/University of Alabama, Huntsville	Geospace Sciences	May 4, 1989	Wallops Island, Virginia	Successful
36.025 GS	Neupert/Goddard Space Flight Center	Solar and Heliospheric Sciences	May 5, 1989	White Sands Missile Range	Successful
36.054 US	Rottman/University of Colorado	Solar and Heliospheric Sciences	June 20, 1989	White Sands Missile Range	Successful
36.043 GG	Smith/Goddard Space Flight Center	UV/Optical Astrophysics	June 27, 1989	White Sands Missile Range	Successful
27.122 UE	Sharp/University of Michigan	Geospace Sciences	July 17, 1989	White Sands Missile Range	Successful
36.059 UL	Judge/University of Southern California	Solar System Exploration	August 23, 1989	White Sands Missile Range	Successful
36.052 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	September 11, 1989	White Sands Missile Range	Successful
36.037 DE	Bernhardt/Naval Research Laboratory	Geospace Sciences	October 23, 1989	Wallops Island, Virginia	Successful
27.123 UG	Cash/University of Colorado	UV/Optical Astrophysics	November 20, 1989	White Sands Missile Range	Successful
12.042 WT	Flowers/Wallops Flight Facility	Test and Support	December 5, 1989	Wallops Island, Virginia	Successful
12.043 WT	Flowers/Wallops Flight Facility	Test and Support	December 21, 1989	Wallops Island, Virginia	Successful

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Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.033 UL	Zipf/University of Pittsburgh	Solar System Exploration	January 23, 1990	White Sands Missile Range	Successful
39.002 UE	Kellogg/University of Minnesota	Geospace Sciences	February 1, 1990	Poker Flat Research Range	Successful vehicle, unsuccessful mission
35.020 UE	Arnoldy/University of New Hampshire	Geospace Sciences	February 23, 1990	Poker Flat Research Range	Successful
36.066 GU	Mentall/Goddard Space Flight Center	Upper Atmosphere	March 9, 1990	White Sands Missile Range	Successful
36.034 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	March 17, 1990	White Sands Missile Range	Successful
40.002 UE	Carlson/University of California, Berkeley	Geospace Sciences	March 22, 1990	Poker Flat Research Range	Successful
31.070 UE	Bering/University of Houston	Geospace Sciences	March 22, 1990	Poker Flat Research Range	Successful vehicle, unsuccessful mission
36.053 DE	McCoy/Naval Research Laboratory	Geospace Sciences	March 30, 1990	White Sands Missile Range	Successful
35.028 CE	Taylor/TRW	Geospace Sciences	April 5, 1990	Wallops Island, Virginia	Successful vehicle, unsuccessful mission

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.067 UG	Cash/University of Colorado	UV/Optical Astrophysics	April 9, 1990	White Sands Missile Range	Successful
36.063 UG	Boyer/University of California, Berkeley	UV/Optical Astrophysics	April 17, 1990	White Sands Missile Range	Successful
36.073 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	April 21, 1990	White Sands Missile Range	Successful
36.074 UG	Cash/University of Colorado	UV/Optical Astrophysics	April 28, 1990	White Sands Missile Range	Successful
33.059 GE	Baker/Goddard Space Flight Center	Geospace Sciences	May 13, 1990	Poker Flat Research Range	Successful
30.035 UE	Hale/Pennsylvania State University	Geospace Sciences	May 13, 1990	Poker Flat Research Range	Successful
33.060 GE	Baker/Goddard Space Flight Center	Geospace Sciences	May 14, 1990	Poker Flat Research Range	Successful
36.069 UL	Barth/University of Colorado	Solar System Exploration	June 1, 1990	White Sands Missile Range	Successful vehicle, unsuccessful mission
27.124 UG	Martin/Columbia University	UV/Optical Astrophysics	July 16, 1990	White Sands Missile Range	Successful
29.028 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	July 30, 1990	Kwajalein, Marshall Islands	Successful
29.029 UE	Kelley/Cornell University	Geospace Sciences	August 2, 1990	Kwajalein, Marshall Islands	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
238.017 UE	Mendillo/Boston University	Geospace Sciences	August 11, 1990	Kwajalein, Marshall Islands	Successful vehicle, unsuccessful mission
38.015 UE	Mendillo/Boston University	Geospace Sciences	August 15, 1990	Kwajalein, Marshall Islands	Successful
38.016 UE	Mendillo/Boston University	Geospace Sciences	August 15, 1990	Kwajalein, Marshall Islands	Successful
36.056 DE	Bernhardt/Naval Research Laboratory	Geospace Sciences	August 22, 1990	Kwajalein, Marshall Islands	Successful
38.018 UE	Mendillo/Boston University	Geospace Sciences	August 22, 1990	Kwajalein, Marshall Islands	Successful
36.072 UL	Judge/University of Southern California	Solar System Exploration	September 4, 1990	White Sands Missile Range	Successful
21.102 IE	Pfaff/Goddard Space Flight Center	Geospace Sciences	October 11, 1990	Andoya, Norway	Successful
36.058 DS	Moses/Naval Research Laboratory	Solar and Heliospheric Sciences	November 21, 1990	White Sands Missile Range	Successful
36.060 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	November 21, 1990	White Sands Missile Range	Successful
36.057 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	January 26, 1991	White Sands Missile Range	Successful
40.001 UE	Kintner/Cornell University	Geospace Sciences	February 12, 1991	Poker Flat Research Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.070 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	February 22, 1991	White Sands Missile Range	Successful
12.044 WT	Kotsifakis/Wallops Flight Facility	Test and Support	March 5, 1991	Wallops Island, Virginia	Successful
36.077 UH	Cash/University of Colorado	High Energy Astrophysics	March 18, 1991	White Sands Missile Range	Successful
36.068 GG	Smith/Goddard Space Flight Center	UV/Optical Astrophysics	March 23, 1991	White Sands Missile Range	Successful
36.078 UL	Barth/University of Colorado	Solar System Exploration	March 30, 1991	White Sands Missile Range	Successful
31.079 UU	Zipf/University of Pittsburgh	Upper Atmosphere	April 25, 1991	Poker Flat Research Range	Successful
31.080 UU	Zipf/University of Pittsburgh	Upper Atmosphere	April 30, 1991	Poker Flat Research Range	Unsuccessful vehicle, unsuccessful mission
36.062 UL	Clarke/University of Michigan	Solar System Exploration	May 4, 1991	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.086 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	May 7, 1991	White Sands Missile Range	Successful
36.049 US	Walker/Stanford University	Solar and Heliospheric Sciences	May 13, 1991	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
24.011 CH	Catura/Lockheed Martin Space Corp.	High Energy Astrophysics	May 20, 1991	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.087 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	July 11, 1991	White Sands Missile Range	Successful
15.249 UE	Ulwick/Utah State University	Geospace Sciences	August 1, 1991	Kiruna, Sweden	Successful
21.103 GE	Goldberg/Goddard Space Flight Center/National Science Foundation	Geospace Sciences	August 1, 1991	Kiruna, Sweden	Successful
31.077 UE	Mitchell/Pennsylvania State University	Geospace Sciences	August 1, 1991	Kiruna, Sweden	Successful
15.250 UE	Ulwick/Utah State University	Geospace Sciences	August 5, 1991	Kiruna, Sweden	Successful
15.251 UE	Ulwick/Utah State University	Geospace Sciences	August 9, 1991	Kiruna, Sweden	Successful
21.104 GE	Goldberg/Goddard Space Flight Center/National Science Foundation	Geospace Sciences	August 9, 1991	Kiruna, Sweden	Successful
31.078 UE	Mitchell/Pennsylvania State University	Geospace Sciences	August 9, 1991	Kiruna, Sweden	Successful
27.129 UE	Sharp/University of Michigan	Geospace Sciences	September 6, 1991	White Sands Missile Range	Successful
38.019 UE	Mendillo/Boston University	Geospace Sciences	December 6, 1991	Wallops Island, Virginia	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
38.020 UE	Mendillo/Boston University	Geospace Sciences	December 6, 1991	Wallops Island, Virginia	Successful
36.079 UG	Green/University of Colorado	UV/Optical Astrophysics	January 11, 1992	White Sands Missile Range	Successful
36.075 UE	Zipf/University of Pittsburgh	Geospace Sciences	January 23, 1992	White Sands Missile Range	Successful
36.096 UH	Cash/University of Colorado	High Energy Astrophysics	January 31, 1992	White Sands Missile Range	Successful
36.089 UG	Green/University of Colorado	UV/Optical Astrophysics	February 22, 1992	White Sands Missile Range	Successful
18.221 UE	Larsen/Clemson University	Geospace Sciences	March 3, 1992	Poker Flat Research Range	Successful
27.130 CE	Kayser/Aerospace	Geospace Sciences	March 3, 1992	Poker Flat Research Range	Successful
18.222 UE	Larsen/Clemson University	Geospace Sciences	March 3, 1992	Poker Flat Research Range	Successful vehicle, unsuccessful mission
18.223 UE	Larsen/Clemson University	Geospace Sciences	March 6, 1992	Poker Flat Research Range	Successful
31.083 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 12, 1992	White Sands Missile Range	Successful
31.082 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 15, 1992	White Sands Missile Range	Successful
36.088 DE	McCoy/Naval Research Laboratory	Geospace Sciences	March 19, 1992	White Sands Missile Range	Successful

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Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
39.003 UE	Raitt/Utah State University	Geospace Sciences	March 29, 1992	Poker Flat Research Range	Successful
36.048 CS	Bruner/Lockheed Martin Space Corp.	Solar and Heliospheric Sciences	May 12, 1992	White Sands Missile Range	Successful
31.084 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 22, 1992	White Sands Missile Range	Successful
18.224 UE	Duncan/Clemson University	Geospace Sciences	May 25, 1992	Camp Tortuguero, Puerto Rico	Successful
31.085 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 27, 1992	White Sands Missile Range	Successful
36.065 DE	Bernhardt/Naval Research Laboratory	Geospace Sciences	May 30, 1992	Camp Tortuguero, Puerto Rico	Successful
36.064 CE	Szusczewicz/Science Applications International Corporation (SAIC)	Geospace Sciences	June 6, 1992	Camp Tortuguero, Puerto Rico	Successful
36.071 UE	Kelley/Cornell University	Geospace Sciences	June 9, 1992	Camp Tortuguero, Puerto Rico	Successful
21.105 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	June 23, 1992	Camp Tortuguero, Puerto Rico	Successful
36.082 DE	Weber/Air Force Geophysical Laboratory	Geospace Sciences	July 2, 1992	Camp Tortuguero, Puerto Rico	Successful
36.083 DE	Weber/Air Force Geophysical Laboratory	Geospace Sciences	July 4, 1992	Camp Tortuguero, Puerto Rico	Successful
36.081 CD	Djuth/Geospace Corp.	Geospace Sciences	July 12, 1992	Camp Tortuguero, Puerto Rico	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
27.133 UE	Sharp/University of Michigan	Geospace Sciences	July 24, 1992	Poker Flat Research Range	Successful
31.081 UU	Sheldon/University of Houston	Upper Atmosphere	August 21, 1992	Wallops Island, Virginia	Successful
36.090 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	August 24, 1992	White Sands Missile Range	Successful
31.093 UU	Zipf/University of Pittsburgh	Upper Atmosphere	August 26, 1992	White Sands Missile Range	Successful
12.045 WT	Balance/Wallops Flight Facility	Test and Support	August 27, 1992	Wallops Island, Virginia	Successful
31.092 UU	Zipf/University of Pittsburgh	Upper Atmosphere	September 1, 1992	White Sands Missile Range	Successful
30.040 UP	Johnson/University of Colorado	Special Projects	September 21, 1992	Wallops Island, Virginia	Successful
36.098 UE	Woods/University of Colorado	Geospace Sciences	October 27, 1992	White Sands Missile Range	Successful
31.094 UU	Zipf/University of Pittsburgh	Upper Atmosphere	December 6, 1992	White Sands Missile Range	Successful
31.095 UU	Zipf/University of Pittsburgh	Upper Atmosphere	December 11, 1992	White Sands Missile Range	Successful
36.085 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	December 15, 1992	White Sands Missile Range	Successful vehicle, unsuccessful mission

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
40.003 UE	Arnoldy/University of New Hampshire	Geospace Sciences	January 1, 1993	Poker Flat Research Range	Unsuccessful vehicle, unsuccessful mission
36.100 NS	Davis/Marshall Space Flight Center	Solar and Heliospheric Sciences	February 8, 1993	White Sands Missile Range	Successful vehicle, unsuccessful mission
31.097 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 8, 1993	White Sands Missile Range	Successful
31.096 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 10, 1993	White Sands Missile Range	Successful
40.004 UE	Carlson/University of California, Berkeley	Geospace Sciences	April 2, 1993	Poker Flat Research Range	Successful
36.099 US	Golub/Smithsonian Astrophysical Observatory	Solar and Heliospheric Sciences	April 12, 1993	White Sands Missile Range	Successful
36.095 UN	Cash/University of Colorado	High Energy Astrophysics	April 17, 1993	White Sands Missile Range	Successful
27.136 UE	Parks/University of Washington	Geospace Sciences	May 6, 1993	Poker Flat Research Range	Successful
31.099 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 14, 1993	White Sands Missile Range	Successful
31.098 UU	Zipf/University of Pittsburgh	Upper Atmosphere	May 19, 1993	White Sands Missile Range	Successful
36.101 UL	Clarke/University of Michigan	Solar System Exploration	June 16, 1993	White Sands Missile Range	Successful
35.029 UE	Kintner/Cornell University	Geospace Sciences	July 22, 1993	Wallops Island, Virginia	Successful vehicle, unsuccessful mission

Table 4–62. NASA Sounding Rocket Launches (1989–1998^{a}) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.105 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	August 17, 1993	White Sands Missile Range	Successful
24.017 CH	Catura/Lockheed Martin Space Corp.	High Energy Astrophysics	August 28, 1993	White Sands Missile Range	Unsuccessful vehicle, unsuccessful mission
31.100 UU	Zipf/University of Pittsburgh	Upper Atmosphere	September 10, 1993	White Sands Missile Range	Successful
31.101 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 13, 1993	White Sands Missile Range	Successful
36.107 UE	Woods/University of Colorado	Geospace Sciences	October 4, 1993	White Sands Missile Range	Successful
33.062 UE	Barth/University of Colorado	Geospace Sciences	October 4, 1993	White Sands Missile Range	Successful vehicle, unsuccessful mission
27.137 UE	Sharp/University of Michigan	Geospace Sciences	January 30, 1994	Poker Flat Research Range	Successful
36.110 IE	Pfaff/Goddard Space Flight Center	Geospace Sciences	February 9, 1994	Andoya, Norway	Successful
36.097 IE	Harris/Naval Research Center	Geospace Sciences	February 10, 1994	White Sands Missile Range	Successful vehicle, unsuccessful mission

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Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
18.233 UE	Larsen/Clemson University	Geospace Sciences	February 12, 1994	Poker Flat Research Range	Successful
18.232 UE	Larsen/Clemson University	Geospace Sciences	February 12, 1994	Poker Flat Research Range	Successful
27.131 CE	Christensen/Aerospace Corp.	Geospace Sciences	February 12, 1994	Poker Flat Research Range	Successful
40.005 UE	Tolbert/University of New Hampshire	Geospace Sciences	March 5, 1994	Poker Flat Research Range	Successful vehicle, unsuccessful mission
31.071 UE	Bering/University of Houston	Geospace Sciences	March 7, 1994	Poker Flat Research Range	Unsuccessful vehicle, unsuccessful mission
36.114 DE	McCoy/Naval Research Laboratory	Geospace Sciences	March 11, 1994	Poker Flat Research Range	Successful
12.046 WT	Balance/Wallops Flight Facility	Test and Support	April 4, 1994	Wallops Island, Virginia	Successful
36.109 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	April 18, 1994	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.123 CS	Bruner/Lockheed Martin Missiles & Space	Solar and Heliospheric Sciences	April 25, 1994	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
31.087 UE	Croskey/Pennsylvania State University	Geospace Sciences	June 22, 1994	Wallops Island, Virginia	Successful vehicle, unsuccessful mission
33.063 UE	Barth/University of Colorado	Geospace Sciences	June 27, 1994	Poker Flat Research Range	Successful
31.086 UE	Croskey/Pennsylvania State University	Geospace Sciences	July 15, 1994	Wallops Island, Virginia	Successful vehicle, unsuccessful mission
30.039 UE	Croskey/Pennsylvania State University	Geospace Sciences	July 16, 1994	Wallops Island, Virginia	Successful vehicle, unsuccessful mission
36.121. CL	Stern/Southwest Research Institute	Solar System Exploration	July 20, 1994	White Sands Missile Range	Successful
36.117 CL	Stern/Southwest Research Institute	Solar System Exploration	August 16, 1994	White Sands Missile Range	Successful
31.102 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 19, 1994	Alcantara, Brazil	Successful
31.103 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 20, 1994	Alcantara, Brazil	Successful
30.041 UP	Riddle/Colorado Space Grant	Special Projects	August 22, 1994	Wallops Island	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
31.105 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 24, 1994	Alcantara, Brazil	Successful
31.104 GE	Goldberg/Goddard Space Flight Center	Geospace Sciences	August 25, 1994	Alcantara, Brazil	Successful
21.110 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	September 9, 1994	Alcantara, Brazil	Successful
31.107 UU	Zipf/University of Pittsburgh	Geospace Sciences	September 12, 1994	White Sands Missile Range	Successful
31.108 UU	Zipf/University of Pittsburgh	Geospace Sciences	September 15, 1994	White Sands Missile Range	Successful
21.111 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	September 21, 1994	Alcantara, Brazil	Successful
18.226 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
18.225 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
18.228 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
18.227 UE	Larsen/Clemson University	Geospace Sciences	September 23, 1994	Alcantara, Brazil	Successful
36.084 UE	Zipf/University of Pittsburgh	Geospace Sciences	October 4, 1994	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
21.112 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	October 6, 1994	Alcantara, Brazil	Successful vehicle, unsuccessful mission
35.030 IE	Labelle/Dartmouth University	Geospace Sciences	October 14, 1994	Alcantara, Brazil	Successful
21.113 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	October 15, 1994	Alcantara, Brazil	Successful
36.124 AE	Woods/National Center for Atmospheric Research	Geospace Sciences	November 3, 1994	White Sands Missile Range	Successful
36.091 US	Walker/Stanford University	Solar and Heliospheric Sciences	November 3, 1994	White Sands Missile Range	Successful
36.013 NP	Ross/Lewis Research Center	Special Projects	November 22, 1994	White Sands Missile Range	Successful
36.050 UG	Nordsieck/University of Wisconsin	UV/Optical Astrophysics	December 3, 1994	White Sands Missile Range	Successful
36.102 UG	Green/University of Colorado	UV/Optical Astrophysics	December 17, 1994	White Sands Missile Range	Successful vehicle, unsuccessful mission
40.006 IE	Kintner/Cornell University	Geospace Sciences	January 25, 1995	Andoya, Norway	Successful
27.138 CE	Christensen/Aero Corp.	Geospace Sciences	February 2, 1995	Poker Flat Research Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
18.230 UE	Larsen/Clemson University	Geospace Sciences	February 2, 1995	Poker Flat Research Range	Successful
40.007 UE	Arnoldy/University of New Hampshire	Geospace Sciences	February 24, 1995	Poker Flat Research Range	Successful
31.106 NP	Schulze/NASA Headquarters	Special Projects	March 15, 1995	Wallops Island, Virginia	Successful
36.120 UE	Zipf/University of Pittsburgh	Geospace Sciences	March 21, 1995	White Sands Missile Range	Successful
31.112 UU	Zipf/University of Pittsburgh	Upper Atmosphere	March 21, 1995	White Sands Missile Range	Successful
35.031 UE	Westcott/University of Alaska	Geospace Sciences	March 26, 1995	Poker Flat Research Range	Successful vehicle, unsuccessful mission
36.104 UL	Clarke/University of Michigan	Solar System Exploration	April 1, 1995	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.137 CL	Stern/Southwest Research Institute	Solar System Exploration	April 15, 1995	White Sands Missile Range	Successful
36.108 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	April 18, 1995	White Sands Missile Range	Successful
36.125 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	May 15, 1995	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.092 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	May 22, 1995	White Sands Missile Range	Successful
33.064 UE	Barth/University of Colorado	Geospace Sciences	June 6, 1995	Poker Flat Research Range	Successful
12.047 WT	Maxfield/Wallops Flight Facility	Test and Support	June 30, 1995	White Sands Missile Range	Successful
31.109 UE	Espy/Utah State University	Geospace Sciences	July 26, 1995	Poker Flat Research Range	Successful vehicle, unsuccessful mission
31.110 UE	Espy/Utah State University	Geospace Sciences	August 9, 1995	Poker Flat Research Range	Successful
36.138 NP	Ross/Lewis Research Center	Special Projects	August 28, 1995	White Sands Missile Range	Successful
36.111 UE	Kelley/Cornell University	Geospace Sciences	September 2, 1995	Wallops Island, Virginia	Successful
36.131 US	Judge/University of Southern California	Solar and Heliospheric Sciences	September 12, 1995	White Sands Missile Range	Successful
36.106 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	October 25, 1995	Woomera, Australia	Successful
36.132 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	October 28, 1995	Woomera, Australia	Successful vehicle, unsuccessful mission
36.116 UG	Green/University of Colorado	UV/Optical Astrophysics	November 5, 1995	Woomera, Australia	Successful

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Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
40.009 IE	James/Communications Research Centre of Canada	Geospace Sciences	November 7, 1995	Poker Flat Research Range	Successful
36.127 UG	Green/University of Colorado	UV/Optical Astrophysics	November 14, 1995	Woomera, Australia	Successful vehicle, unsuccessful mission
36.128 UG	Nordsieck/University of Wisconsin	UV/Optical Astrophysics	November 19, 1995	Woomera, Australia	Successful
36.126 UG	Green/University of Colorado	UV/Optical Astrophysics	November 20, 1995	Woomera, Australia	Successful
18.231 UE	Larsen/Clemson University	Geospace Sciences	November 24, 1995	Poker Flat Research Range	Successful
18.229 UE	Larsen/Clemson University	Geospace Sciences	November 27, 1995	Poker Flat Research Range	Successful
27.139 CE	Christensen/Aerospace Corp.	Geospace Sciences	November 27, 1995	Poker Flat Research Range	Successful
27.132 UH	McCammon/University of Wisconsin	High Energy Astrophysics	December 4, 1995	White Sands Missile Range	Successful vehicle/ unsuccessful mission
36.143 UE	Zipf/University of Pittsburgh	Geospace Sciences	February 23, 1996	White Sands Missile Range	Successful
36.145 NP	Ross/Lewis Research Center	Special Projects	February 23, 1996	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.122 UG	Green/University of Colorado	UV/Optical Astrophysics	March 6, 1996	White Sands Missile Range	Successful
27.140 UH	McCammon/University of Wisconsin	High Energy Astrophysics	June 4, 1996	White Sands Missile Range	Successful
36.134 UR	Lange/California Institute of Technology	Upper Atmosphere	June 17, 1996	White Sands Missile Range	Successful
36.118 NP	Olson/Lewis Research Center	Special Projects	June 20, 1996	White Sands Missile Range	Successful
36.147 NP	Judge/University of Southern California	Solar and Heliospheric Sciences	June 26, 1996	White Sands Missile Range	Successful
36.113 UG	Martin/Columbia University	UV/Optical Astrophysics	July 14, 1996	White Sands Missile Range	Successful
36.148 CL	Stern/Southwest Research Center	Solar System Exploration	July 26, 1996	White Sands Missile Range	Successful
31.114 UP	Riddle/University of Colorado	Special Projects	August 12, 1996	Wallops Island, Virginia	Successful
36.130 NS	Davis/Marshall Space Flight Center	Solar and Heliospheric Sciences	August 20, 1996	White Sands Missile Range	Successful vehicle, unsuccessful mission
36.154 NP	Olson/Lewis Research Center	Special Projects	October 16, 1996	White Sands Missile Range	Successful
36.115 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	October 21, 1996	White Sands Missile Range	Successful
36.149 UL	Clare/University of Michigan	Solar System Exploration	October 29, 1996	White Sands Missile Range	Successful
36.142 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	November 13, 1996	White Sands Missile Range	Successful

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Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
41.005 GP	Deily/Goddard Space Flight Center	Special Projects	November 17, 1996	White Sands Missile Range	Successful
40.010 UE	Arnoldy/University of New Hampshire	Geospace Sciences	February 10, 1997	Poker Flat Research Range	Successful
40.011 UE	Torbert/University of New Hampshire	Geospace Sciences	February 11, 1997	Poker Flat Research Range	Successful
36.161 NP	Olson/Lewis Research Center	Special Projects	February 26, 1997	White Sands Missile Range	Successful
36.139 UE	Parks/University of Washington	Geospace Sciences	March 13, 1997	Poker Flat Research Range	Successful
36.158 UL	Green/University of Colorado	Solar System Exploration	March 25, 1997	White Sands Missile Range	Successful
36.155 CL	Stern/Southwest Research Institute	Solar System Exploration	March 30, 1997	White Sands Missile Range	Successful
36.156 UG	Feldman/The Johns Hopkins University	UV/Optical Astrophysics	April 6, 1997	White Sands Missile Range	Successful
36.157 UL	Harris/University of Wisconsin	Solar System Exploration	April 8, 1997	White Sands Missile Range	Successful
36.093 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	May 2, 1997	White Sands Missile Range	Successful
36.133 UG	Chakrabarti/Boston University	UV/Optical Astrophysics	May 8, 1997	White Sands Missile Range	Successful
36.135 AE	Woods/National Center for Atmospheric Research	Geospace Sciences	May 15, 1997	White Sands Missile Range	Successful
41.013 DT	Bowman/Department of the Army	Test and Support	May 23, 1997	Wallops Island, Virginia	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.163 UR	Lange/California Institute of Technology	Upper Atmosphere	May 29, 1997	White Sands Missile Range	Successful
41.011 UE	Ulwick/Utah State University	Geospace Sciences	August 8, 1997	Wallops Island, Virginia	Unsuccessful
21.120 NE	Mlynczak/Langley Research Center	Geospace Sciences	August 8, 1997	White Sands Missile Range	Successful
36.164 US	Judge/University of Southern California	Solar and Heliospheric Sciences	August 11, 1997	White Sands Missile Range	Successful
41.014 DT	Bowman/Department of the Army	Test and Support	September 2, 1997	Woomera, Australia	Successful
41.015 DT	Bowman/Department of the Army	Test and Support	September 5, 1997	Woomera, Australia	Successful
41.016 DT	Bowman/Department of the Army	Test and Support	September 10, 1997	Woomera, Australia	Successful
36.169 NM	Olson/Lewis Research Center	Microgravity Research	September 10, 1997	White Sands Missile Range	Successful
36.165 NP	Ross/Lewis Research Center	Special Projects	September 10, 1997	White Sands Missile Range	Successful
41.017 DT	Bowman/Department of the Army	Test and Support	September 11, 1997	Woomera, Australia	Successful
36.144 UE	Zipf/University of Pittsburgh	Geospace Sciences	September 19, 1997	White Sands Missile Range	Successful
36.140 DS	Brueckner/Naval Research Laboratory	Solar and Heliospheric Sciences	September 30, 1997	White Sands Missile Range	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.129 DS	Moses/Naval Research Laboratory	Solar and Heliospheric Sciences	October 16, 1997	White Sands Missile Range	Successful
41.004 IE	Kane/Pennsylvania State University	Geospace Sciences	November 5, 1997	Andoya, Norway	Successful
36.080 UG	Chakrabarti/Boston University	UV/Optical Astrophysics	November 14, 1997	White Sands Missile Range	Successful
36.167 GS	Davila/Goddard Space Flight Center	Solar and Heliospheric Sciences	November 18, 1997	White Sands Missile Range	Successful
36.153 IE	Maynard/Mission Research Corp.	Geospace Sciences	December 2, 1997	Svalbard, Norway	Successful
36.152	Pfaff/Goddard Space Flight Center	Geospace Sciences	December 3, 1997	Svalbard, Norway	Successful
21.117	Kelley/Cornell University	Geospace Sciences	February 20, 1998	Camp Tortuguero, Puerto Rico	Successful
21.119 UE	Larsen/Clemson University	Geospace Sciences	February 20, 1998	Camp Tortuguero, Puerto Rico	Successful
21.118 UE	Larsen/Clemson University	Geospace Sciences	February 25, 1998	Camp Tortuguero, Puerto Rico	Successful
33.067 UE	Larsen/Clemson University	Geospace Sciences	February 25, 1998	Camp Tortuguero, Puerto Rico	Successful
41.008 UE	Ulwick/Utah State University	Geospace Sciences	February 25, 1998	Camp Tortuguero, Puerto Rico	Successful
21.114 UE	Earle/University of Texas at Dallas	Geospace Sciences	March 7, 1998	Camp Tortuguero, Puerto Rico	Successful

Table 4–62. NASA Sounding Rocket Launches (1989–1998[a]) (Continued)

Mission Designation	Experimenter/Organization	Discipline	Date	Range	Results
36.159 UE	Kelley/Cornell University	Geospace Sciences	March 11, 1998	Camp Tortuguero, Puerto Rico	Successful
21.115 GE	Pfaff/Goddard Space Flight Center	Geospace Sciences	March 25, 1998	Camp Tortuguero, Puerto Rico	Successful
36.177 UG	Chakrabarti/Boston University	UV/Optical Astrophysics	April 18, 1998	White Sands Missile Range	Successful
36.160 UG	Green/University of Colorado	UV/Optical Astrophysics	April 18, 1998	White Sands Missile Range	Successful
30.042 NP	Koehler/NASA Wallops Flight Facility	Special Projects	May 6, 1998	Wallops Island, Virginia	Successful
36.175 UR	Lange/California Institute of Technology	Upper Atmosphere	May 22, 1998	White Sands Missile Range	Successful
31.111 UP	Basciano/University of Cincinnati	Special Projects	June 17, 1998	Wallops Island, Virginia	Successful
36.176 UH	Garmire/Pennsylvania State University	High Energy Astrophysics	August 15, 1998	White Sands Missile Range	Successful
36.150 NP	Murbach/Ames Research Center	Special Projects	September 18, 1998	White Sands Missile Range	Successful
36.171 CS	Hassler/Southwest Research Institute	Solar and Heliospheric Sciences	November 2, 1998	White Sands Missile Range	Successful
36.178 NM	Ross/Lewis Research Center	Microgravity Research	November 18, 1998	White Sands Missile Range	Successful vehicle, unsuccessful mission

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[a] Goddard Space Flight Center, Wallops Flight Facility, "NASA Research Carriers Program Sounding Rocket and Balloon Projects Schedule," October 2001.

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Table 4–63. NASA Balloon Flights (1989–1998[a])

Experimenter/Organization	Discipline	Date	Site	Results
Prince/California Institute of Technology	Gamma Ray/X-Ray Astrophysics	April 3, 1989	Alice Springs, Australia	Successful
Sofia/Yale University	Solar and Heliospheric Physics	April 18, 1989	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	April 19, 1989	Ft. Sumner, New Mexico	Successful
Grindlay/Harvard University	Gamma Ray/X-Ray Astrophysics	May 8, 1989	Alice Springs, Australia	Successful
Traub/Smithsonian Astrophysical Observatory	Upper Atmosphere Research	May 15, 1989	Palestine, Texas	Successful
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	May 21, 1989	Alice Springs, Australia	Successful
Waters/Jet Propulsion Laboratory	Upper Atmosphere Research	May 27, 1989	Palestine, Texas	Successful
Heaps/Goddard Space Flight Center	Upper Atmosphere Research	June 6, 1989	Palestine, Texas	Balloon successful, mission unsuccessful
Diagnostic, Anderson/National Scientific Balloon Facility, Harvard University	Test Flight	July 28, 1989	Palestine, Texas	Successful
Mauersberger/University of Minnesota	Upper Atmosphere Research	July 31, 1989	Palestine, Texas	Successful
Diagnostic, Anderson/National Scientific Balloon Facility, Harvard University	Test Flight	August 25, 1989	Palestine, Texas	Successful
Zander/University of Liege	Upper Atmosphere Research	August 28, 1989	Palestine, Texas	Successful
Beatty/Boston University	Cosmic Ray Astrophysics	September 1, 1989	Prince Albert, Canada	Successful
Golden, Streitmatter/New Mexico State University, Goddard Space Flight Center	Cosmic Ray Astrophysics	September 5, 1989	Prince Albert, Canada	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Traub, Waters/Smithsonian Astrophysical Observatory, Jet Propulsion Laboratory	Upper Atmosphere Research	September 26, 1989	Ft. Sumner, New Mexico	Successful
White/University of California, Riverside	Gamma Ray/X-Ray Astrophysics	September 29, 1989	Ft. Sumner, New Mexico	Successful
Meyer/Massachusetts Institute of Technology	Upper Atmosphere Research	October 6, 1989	Ft. Sumner, New Mexico	Successful
Farmer/Jet Propulsion Laboratory	Upper Atmosphere Research	October 8, 1989	Ft. Sumner, New Mexico	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	October 13, 1989	Ft. Sumner, New Mexico	Successful
Mauersberger/University of Minnesota	Upper Atmosphere Research	October 24, 1989	Ft. Sumner, New Mexico	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	November 2, 1989	Ft. Sumner, New Mexico	Successful
Richards/University of California, Berkeley	Upper Atmosphere Research	November 15, 1989	Ft. Sumner, New Mexico	Successful
Lubin/University of California, Santa Barbara	Upper Atmosphere Research	November 19, 1989	Ft. Sumner, New Mexico	Successful
Stuchlik, LDB Subsystems Test/Goddard Space Flight Center–Wallops Flight Facility	Test Flight	January 1, 1990	McMurdo Station, Antarctica	Balloon successful, mission unsuccessful
Stuchlik, LDB Subsystems Test/Goddard Space Flight Center–Wallops Flight Facility	Test Flight	January 8, 1990	McMurdo Station, Antarctica	Balloon successful, mission unsuccessful
Sofia/Yale University	Solar and Heliospheric Physics	May 4, 1990	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	May 5, 1990	Ft. Sumner, New Mexico	Successful
Stachnik-Traub/Jet Propulsion Laboratory	Upper Atmosphere Research	May 12, 1990	Ft. Sumner, New Mexico	Balloon and mission unsuccessful
Meyer/Massachusetts Institute of Technology	UV/Optical Astrophysics	May 31, 1990	Ft. Sumner, New Mexico	Successful
Teegarden/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	May 31, 1990	Ft. Sumner, New Mexico	Successful
Stachnik-Traub/Jet Propulsion Laboratory, Smithsonian Astrophysical Observatory	Upper Atmosphere Research	June 4, 1990	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	June 4, 1990	Palestine, Texas	Successful
Lubin/University of California, Santa Barbara	UV/Optical Astrophysics	July 2, 1990	Palestine, Texas	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	July 10, 1990	Ft. Sumner, New Mexico	Successful
Bawcom, Diagnostic/National Scientific Balloon Facility	Test Flight	July 28, 1990	Ft. Sumner, New Mexico	Successful
Streitmatter/Goddard Space Flight Center	Cosmic Ray Astrophysics	August 9, 1990	Lynn Lake, Canada	Balloon successful, mission unsuccessful
Simpson, Diagnostic/Wallops Flight Facility	Test Flight	August 16, 1990	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 26, 1990	Lynn Lake, Canada	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Zander/University of Liege	Upper Atmosphere Research	August 29, 1990	Palestine, Texas	Successful
Stuchlik/LDB Subsystems	Test Flight	September 2, 1990	Palestine, Texas	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 19, 1990	Ft. Sumner, New Mexico	Balloon and mission unsuccessful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 26, 1990	Ft. Sumner, New Mexico	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	September 27, 1990	Ft. Sumner, New Mexico	Successful
Russell/Langley Research Center	Upper Atmosphere Research	October 9, 1990	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	October 11, 1990	Ft. Sumner, New Mexico	Successful
Lubin/University of California, Santa Barbara	Infrared/Submillimeter Astrophysics	October 23, 1990	Ft. Sumner, New Mexico	Successful
Bawcom/National Scientific Balloon Facility	Test Flight	October 28, 1990	Ft. Sumner, New Mexico	Successful
Holzworth/University of Washington	Geospace Sciences	October 30, 1990	Ft. Sumner, New Mexico	Successful
Lin/University of California, Berkeley	Solar and Heliospheric Physics	December 20, 1990	Antarctica	Balloon successful, mission unsuccessful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	January 30, 1991	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Holzworth/University of Washington	Geospace Sciences	February 20, 1991	New Zealand	Balloon successful, mission unsuccessful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	February 23, 1991	Palestine, Texas	Successful
Bawcom/ Diagnostic/National Scientific Balloon Facility	Test Flight	March 29, 1991	Ft. Sumner, New Mexico	Successful
Anderson/Harvard University	Upper Atmosphere Research	March 31, 1991	Ft. Sumner, New Mexico	Successful
Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	April 9, 1991	Daggett, California	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	May 5, 1991	Ft. Sumner, New Mexico	Successful
Bawcom/ Diagnostic/National Scientific Balloon Facility	Test Flight	May 8, 1991	Ft. Sumner, New Mexico	Successful
Lubin/University of California, Santa Barbara	Infrared/Submillimeter Astrophysics	May 26, 1991	Palestine, Texas	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	May 26, 1991	Palestine, Texas	Successful
Lubin/University of California, Santa Barbara	Infrared/Submillimeter Astrophysics	June 4, 1991	Palestine, Texas	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	June 12, 1991	Palestine, Texas	Successful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	June 16, 1991	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	June 17, 1991	Palestine, Texas	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Simpson/NSP/Wallops Flight Facility	Test Flight	June 18, 1991	Ft. Sumner, New Mexico	Balloon failed, mission successful
Hays/University of Michigan	Upper Atmosphere Research	June 19, 1991	Palestine, Texas	Successful
Beatty/Boston University	Cosmic Ray Astrophysics	July 25, 1991	Lynn Lake, Canada	Successful
Klarmann/Washington University	Cosmic Ray Astrophysics	August 9, 1991	Lynn Lake, Canada	Successful
Stuchlik/LDB/Wallops Flight Facility	Test Flight	September 10, 1991	Palestine, Texas	Successful
Mauersberger/University of Minnesota	Upper Atmosphere Research	September 17, 1991	Ft. Sumner, New Mexico	Successful
Golden/New Mexico State University	Cosmic Ray Astrophysics	September 23, 1991	Ft. Sumner, New Mexico	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	September 25, 1991	Ft. Sumner, New Mexico	Successful
Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	October 1, 1991	Ft. Sumner, New Mexico	Successful
Bawcom/Diagnostic/National Scientific Balloon Facility	Test Flight	November 2, 1991	Palestine, Texas	Successful
Holzworth, Diagnostics/University of Washington	Test Flight	November 8, 1991	Ft. Sumner, New Mexico	Successful
Salamon/University of Utah	Cosmic Ray Astrophysics	December 16, 1991	Antarctica	Successful
Lin/University of California, Berkeley	Solar and Heliospheric Physics	January 10, 1992	Antarctica	Successful
Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	February 20, 1992	Daggett, California	Successful
Anderson/Harvard University	Upper Atmosphere Research	February 22, 1992	Sondre Stronfjord, Greenland	Balloon successful, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Anderson/Harvard University	Upper Atmosphere Research	March 1, 1992	Sondre Stronfjord, Greenland	Successful
Simpson, OZP/NWallops Flight Facility	Test Flight	March 9, 1992	Daggett, California	Successful
Anderson/Harvard University	Upper Atmosphere Research	March 11, 1992	Sondre Stronfjord, Greenland	Successful
Simpson, NSP/Wallops Flight Facility	Test Flight	April 12, 1992	Palestine, Texas	Mission successful, balloon unsuccessful,
Teegarden/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	April 26, 1992	Alice Springs, Australia	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	April 27, 1992	Alice Springs, Australia	Balloon successful, mission unsuccessful
Nolt/Langley Research Center	Upper Atmosphere Research	May 4, 1992	Ft. Sumner, New Mexico	Successful
Zander/University of Liege	Upper Atmosphere Research	May 4, 1992	Ft. Sumner, New Mexico	Successful
Teegarden/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	May 7, 1992	Alice Springs, Australia	Successful
Low/University of Arizona	Infrared/Submillimeter Astrophysics	May 8, 1992	Alice Springs, Australia	Balloon successful, mission failed
Low/University of Arizona	Infrared/Submillimeter Astrophysics	May 24, 1992	Alice Springs, Australia	Successful
Traub/Smithsonian Astrophysical Observatory	Upper Atmosphere Research	May 29, 1992	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	June 1, 1992	Alice Springs, Australia	Successful
Silverberg/Goddard Space Flight Center	Infrared/Submillimeter Astrophysics	June 5, 1992	Palestine, Texas	Successful
Streitmatter/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 17, 1992	Lynn Lake, Canada	Successful
Holzworth/University of Washington	Upper Atmosphere Research	July 24, 1992	Wallops Island, VA	Balloon succeeded, mission unsuccessful
Murcray/University of Denver	Upper Atmosphere Research	July 24, 1992	Palestine, Texas	Successful
Holzworth/University of Washington	Upper Atmosphere Research	July 31, 1992	Wallops Island, VA	Balloon and mission unsuccessful
Meyer/University of Chicago	Cosmic Ray Astrophysics	August 2, 1992	Lynn Lake, Canada	Balloon and mission unsuccessful
Holzworth/University of Washington	Upper Atmosphere Research	August 11, 1992	Wallops Island, VA	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 25, 1992	Lynn Lake, Canada	Successful
Webster/Jet Propulsion Laboratory	Upper Atmosphere Research	August 26, 1992	Palestine, Texas	Successful
Gregory, LDB/National Scientific Balloon Facility	Test Flight	August 29, 1992	Palestine, Texas	Successful
Simpson, OZP/Wallops Flight Facility	Test Flight	September 6, 1992	Lynn Lake, Canada	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	September 14, 1992	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Stachnik, Traub/Jet Propulsion Laboratory, Smithsonian Astrophysical Observatory	Upper Atmosphere Research	September 29, 1992	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	September 30, 1992	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	October 16, 1992	Ft. Sumner, New Mexico	Successful
Robbins/Wallops Flight Facility	Test Flight	November 5, 1992	Ft. Sumner, New Mexico	Successful
Holzworth/University of Washington	Upper Atmosphere Research	November 10, 1992	New Zealand	Successful
Holzworth/University of Washington	Upper Atmosphere Research	November 19, 1992	New Zealand	Successful
Holzworth/University of Washington	Upper Atmosphere Research	November 21, 1992	New Zealand	Mission successful, balloon unsuccessful
Holzworth/University of Washington	Upper Atmosphere Research	November 30, 1992	New Zealand	Successful
Holzworth/University of Washington	Upper Atmosphere Research	December 6, 1992	New Zealand	Successful
Trombka/Goddard Space Flight Center	Solar and Heliospheric Physics	December 12, 1992	Antarctica	Successful
Lin/University of California, Berkeley	Solar and Heliospheric Physics	December 31, 1992	Antarctica	Balloon successful, mission failed
Traub/Smithsonian Astrophysical Observatory	Upper Atmosphere Research	March 23, 1993	Daggett, California	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	April 3, 1993	Daggett, California	Successful
Murcray/University of Denver	Upper Atmosphere Research	April 7, 1993	Daggett, California	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Parks/University of Washington	Geospace Sciences	May 1, 1993	Fairbanks, Alaska	Balloon successful, mission failed
Bell/Wallops Flight Facility	Test Flight	May 3, 1993	Ft. Sumner, New Mexico	Successful
Parks/University of Washington	Geospace Sciences	May 6, 1993	Fairbanks, Alaska	Successful
Lubin, Seiffert/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	May 21, 1993	Palestine, Texas	Successful
Murcray/University of Denver	Upper Atmosphere Research	May 25, 1993	Palestine, Texas	Balloon successful, mission failed
Nolt/Langley Research Center	Upper Atmosphere Research	May 31, 1993	Ft. Sumner, New Mexico	Successful
Zander/University of Liege	Upper Atmosphere Research	June 11, 1993	Ft. Sumner, New Mexico	Successful
Grindlay/Harvard University	Gamma Ray/X-Ray Astrophysics	June 13, 1993	Palestine, Texas	Successful
Lubin, Meinhold/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	June 16, 1993	Palestine, Texas	Successful
Crannell/Goddard Space Flight Center	Solar and Heliospheric Physics	June 22, 1993	Palestine, Texas	Successful
Murcray/University of Denver	Upper Atmosphere Research	July 19, 1993	Palestine, Texas	Successful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 26, 1993	Lynn Lake, Canada	Successful
Lubin, Koch/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	August 12, 1993	Palestine, Texas	Balloon succeeded, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Weidenbeck/Jet Propulsion Laboratory	Cosmic Ray Astrophysics	August 13, 1993	Lynn Lake, Canada	Balloon succeeded, mission unsuccessful
LDBV, Simpson/Wallops Flight Facility	Test Flight	August 17, 1993	Lynn Lake, Canada	Successful
Holzworth/University of Washington	Geospace Sciences	August 18, 1993	Wallops Flight Facility	Successful
LDB, Kubara/Wallops Flight Facility	Test Flight	September 2, 1993	Lynn Lake, Canada	Balloon and mission unsuccessful
Golden/New Mexico State University	Cosmic Ray Astrophysics	September 9, 1993	Ft. Sumner, New Mexico	Successful
Prince/California Institute of Technology	Gamma Ray/X-Ray Astrophysics	September 14, 1993	Ft. Sumner, New Mexico	Successful
Tueller/Goddard SpaceFlight Center	Gamma Ray/X-Ray Astrophysics	September 23, 1993	Ft. Sumner, New Mexico	Successful
Toon, Stachnik/Jet Propulsion Laboratory	Upper Atmosphere Research	September 25, 1993	Ft. Sumner, New Mexico	Successful
Gregory/University of Alabama	Cosmic Ray Astrophysics	September 29, 1993	Ft. Sumner, New Mexico	Successful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	October 27, 1993	Ft. Sumner, New Mexico	Successful
Wilkes/University of Washington	Cosmic Ray Astrophysics	December 14, 1993	Antarctica	Balloon successful, mission unsuccessful
Wilkes/University of Washington	Cosmic Ray Astrophysics	January 2, 1994	Antarctica	Successful
Rust/Applied Physics Lab	Solar and Heliospheric Physics	January 23, 1994	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Muller/University of Chicago	Cosmic Ray Astrophysics	May 30, 1994	Ft. Sumner, New Mexico	Successful
Nolt/Langley Research Center	Upper Atmosphere Research	May 15, 1994	Ft. Sumner, New Mexico	Successful
Traub, Toon/Smithsonian Astrophysical Observatory, Jet Propulsion Laboratory	Upper Atmosphere Research	May 22, 1994	Ft. Sumner, New Mexico	Successful
Holzworth/University of Washington	Geospace Sciences	May 26, 1994	Wallops Flight Facility	Balloon succeeded, mission unsuccessful
Holzworth/University of Washington	Geospace Sciences	May 26, 1994	Wallops Flight Facility	Successful
Silverberg/Goddard Space Flight Center	IR/Submillimeter Astrophysics	June 2, 1994	Palestine, Texas	Successful
Lubin, Seiffert/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	June 7, 1994	Palestine, Texas	Successful
Lubin, Sieffert/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	June 20, 1994	Palestine, Texas	Successful
Holzworth/University of Washington	Geospace Sciences	June 22, 1994	Wallops Flight Facility	Successful
Murcray/University of Denver	Upper Atmosphere Research	July 10, 1994	Palestine, Texas	Balloon succeeded, mission unsuccessful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	August 1, 1994	Lynn Lake, Canada	Successful
Golden/New Mexico State University	Cosmic Ray Astrophysics	August 8, 1994	Lynn Lake, Canada	Successful
Cooper, LDB/Wallops Flight Facility	Test Flight	August 17, 1994	Lynn Lake, Canada	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Lubin, Koch/University of California, Santa Barbara	Gamma Ray/X-Ray Astrophysics	August 27, 1994	Palestine, Texas	Balloon succeeded, mission unsuccessful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 28, 1994	Lynn Lake, Canada	Successful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	September 2, 1994	Palestine, Texas	Balloon and mission unsuccessful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	September 10, 1994	Palestine, Texas	Successful
Sofia/Yale University	Solar and Heliospheric Physics	September 26, 1994	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	October 9, 1994	Ft. Sumner, New Mexico	Successful
Klein/National Scientific Balloon Facility	Test Flight	October 19, 1994	Ft. Sumner, New Mexico	Successful
Wilkes/University of Washington	Cosmic Ray Astrophysics	December 21, 1994	Antarctica	Successful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	January 8, 1995	Antarctica	Successful
Raque/Wallops Flight Facility	Test Flight	April 1, 1995	Ft. Sumner, New Mexico	Successful
Parsons/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	June 1, 1995	Palestine, Texas	Successful
Silverberg/Goddard Space Flight Center	IR/Submillimeter Astrophysics	June 1, 1995	Palestine, Texas	Successful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 26, 1995	Lynn Lake, Canada	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	August 23, 1995	Lynn Lake, Canada	Successful
Sandy/Virginia Space Grant Consortium	Special Projects	August 23, 1995	Wallops Flight Facility	Successful
Lande/University of Pennsylvania	Special Projects	August 23, 1995	Wallops Flight Facility	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Binns/Washington University	Cosmic Ray Astrophysics	August 26, 1995	Lynn Lake, Canada	Balloon and mission unsuccessful
Richards/University of California, Berkeley	IR/Submillimeter Astrophysics	September 3, 1995	Palestine, Texas	Successful
Sood/University of New South Wales	Special Projects	September 26, 1995	Alice Springs, Australia	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 27, 1995	Ft. Sumner, New Mexico	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	September 28, 1995	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	October 1, 1995	Ft. Sumner, New Mexico	Successful
Tueller/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	October 4, 1995	Alice Springs, Australia	Balloon and mission unsuccessful
Prince/California Institute of Technology	Gamma Ray/X-Ray Astrophysics	October 6, 1995	Alice Springs, Australia	Successful
Frontera/Instituto Di Tecnologie e Studio Delle Radiaziioni Extraterrestri (TESRE)	Gamma Ray/X-Ray Astrophysics	October 6, 1995	Ft. Sumner, New Mexico	Successful
Murcray/University of Denver	Upper Atmosphere Research	October 10, 1995	Ft. Sumner, New Mexico	Successful
Haymes/Rice University	Gamma Ray/X-Ray Astrophysics	October 14, 1995	Ft. Sumner, New Mexico	Successful
Hailey/Lawrence Livermore National Laboratory	Gamma Ray/X-Ray Astrophysics	October 16, 1995	Alice Springs, Australia	Successful
Tueller/ Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	October 24, 1995	Alice Springs, Australia	Successful
Tueller/Goddard Space Flight Center	Gamma Ray/X-Ray Astrophysics	November 14, 1995	Alice Springs, Australia	Successful
Meyer/University of Chicago	IR/Submillimeter Astrophysics	December 9, 1995	Ft. Sumner, New Mexico	Successful
Wilkes/University of Washington	Cosmic Ray Astrophysics	December 19, 1995	Antarctica	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	**Discipline**	**Date**	**Site**	**Results**
Rust/Applied Physics Laboratory	Solar and Heliospheric Physics	January 7, 1996	Antarctica	Successful
Lubin/University of California, Santa Barbara	IR/Submillimeter Astrophysics	February 11, 1996	Ft. Sumner, New Mexico	Successful
Lubin, Meinhold/University of California, Santa Barbara	IR/Submillimeter Astrophysics	June 2, 1996	Ft. Sumner, New Mexico	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	June 10, 1996	Ft. Sumner, New Mexico	Successful
Wilkinson/Princeton University	IR/Submillimeter Astrophysics	June 17, 1996	Palestine, Texas	Successful
Anspaugh/Jet Propulsion Laboratory	Special Projects	June 30, 1996	Palestine, Texas	Successful
Rotter/National Scientific Balloon Facility	Test Flight	July 3, 1996	Palestine, Texas	Successful
Adams/Naval Research Laboratory	Cosmic Ray Astrophysics	July 4, 1996	Fairbanks, Alaska	Balloon and mission unsuccessful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	July 24, 1996	Lynn Lake, Canada	Balloon successful, mission unsuccessful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 8, 1996	Palestine, Texas	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	September 21, 1996	Ft. Sumner, New Mexico	Successful
Buisson/Centre National d'Etudes Spatiales (CNES)	Gamma Ray/X-Ray Astrophysics	September 22, 1996	Ft. Sumner, New Mexico	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	September 28, 1996	Ft. Sumner, New Mexico	Successful
Sofia/Yale University	Solar and Heliospheric Physics	October 10, 1996	Ft. Sumner, New Mexico	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	October 13, 1996	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Anspaugh/Jet Propulsion Laboratory	Special Projects	October 23, 1996	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful
Wilkinson/Princeton University	IR/Submillimeter Astrophysics	November 9, 1996	Ft. Sumner, New Mexico	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	February 14, 1997	Brazil	Successful
Orr, Simpson/National Scientific Balloon Facility, Wallops Flight Facility	Test Flight	March 30, 1997	Ft. Sumner, New Mexico	Successful
Traub/Jet Propulsion Laboratory	Upper Atmosphere Research	April 30, 1997	Fairbanks, Alaska	Successful
Grindlay/Harvard University	Gamma Ray/X-Ray Astrophysics	May 7, 1997	Ft. Sumner, New Mexico	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	May 8, 1997	Fairbanks, Alaska	Successful
Parnell/Marshall Space Flight Center	Cosmic Ray Astrophysics	May 20, 1997	Ft. Sumner, New Mexico	Successful
Stochaj/New Mexico State University	Cosmic Ray Astrophysics	May 24, 1997	Ft. Sumner, New Mexico	Balloon successful, mission failed
Cheng/Goddard Space Flight Center	IR/Submillimeter Astrophysics	June 2, 1997	Palestine, Texas	Successful
Anspaugh/Jet Propulsion Laboratory	Special Projects	June 11, 1997	Palestine, Texas	Successful
Orr, Simpson/National Scientific Balloon Facility, Wallops Flight Facility	Test Flight	June 23, 1997	Fairbanks, Alaska	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	June 30, 1997	Fairbanks, Alaska	Successful
Toon/Jet Propulsion Laboratory	Upper Atmosphere Research	July 8, 1997	Fairbanks, Alaska	Successful
Aprile/Columbia University	Gamma Ray/X-Ray Astrophysics	July 25, 1997	Palestine, Texas	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	**Discipline**	**Date**	**Site**	**Results**
Ormes, Orito/Goddard Space Flight Center, High Energy Accelerator Research Organization (KEK-Japan)	Cosmic Ray Astrophysics	July 28, 1997	Lynn Lake, Canada	Successful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 2, 1997	Palestine, Texas	Successful
Lange/California Institute of Technology	IR/Submillimeter Astrophysics	August 13, 1997	Palestine, Texas	Balloon and mission unsuccessful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 14, 1997	Palestine, Texas	Balloon succeeded, mission unsuccessful
Anspaugh/Jet Propulsion Laboratory	Special Projects	August 24, 1997	Palestine, Texas	Successful
Aprile/Columbia University	Gamma Ray/X-Ray Astrophysics	August 25, 1997	Palestine, Texas	Successful
Lange/California Institute of Technology	IR/Submillimeter Astrophysics	August 30, 1997	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	September 2, 1997	Lynn Lake, Canada	Successful
Binns/Washington University	Cosmic Ray Astrophysics	September 24, 1997	Ft. Sumner, New Mexico	Successful
Muller/University of Chicago	Cosmic Ray Astrophysics	October 4, 1997	Ft. Sumner, New Mexico	Successful
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	October 15, 1997	Ft. Sumner, New Mexico	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	November 11, 1997	Brazil	Successful
Brune/Pennsylvania State University	Upper Atmosphere Research	November 20, 1997	Brazil	Successful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	January 7, 1998	Antarctica	Balloon and mission failed

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Candeleria/National Scientific Balloon Facility	Test Flight	February 11, 1998	Palestine, Texas	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	February 18, 1998	Palestine, Texas	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	February 20, 1998	Palestine, Texas	Successful
Farman/National Scientific Balloon Facility	Test Flight	March 20, 1998	Ft. Sumner, New Mexico	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	March 24, 1998	Palestine, Texas	Successful
Farman/National Scientific Balloon Facility	Test Flight	April 9, 1998	Ft. Sumner, New Mexico	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	April 10, 1998	Palestine, Texas	Successful
Candeleria/National Scientific Balloon Facility	Test Flight	April 19, 1998	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	April 22, 1998	Ft. Sumner, New Mexico	Successful
Stochaj/New Mexico State University	Cosmic Ray Astrophysics	May 16, 1998	Ft. Sumner, New Mexico	Balloon successful, mission unsuccessful
Brune/Pennsylvania State University	Upper Atmosphere Research	May 18, 1998	Ft. Sumner, New Mexico	Successful
Matteson/University of California, San Diego	Gamma Ray/X-Ray Astrophysics	May 21, 1998	Ft. Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	Discipline	Date	Site	Results
Pickett/Jet Propulsion Laboratory	Upper Atmosphere Research	May 24, 1998	Ft. Sumner, New Mexico	Successful
Stochaj/New Mexico State University	Cosmic Ray Astrophysics	May 28, 1998	Ft. Sumner, New Mexico	Successful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	June 18, 1998	Fairbanks, Alaska	Balloon succeeded, mission unsuccessful
Lin/University of California, Berkeley	Gamma Ray/X-Ray Astrophysics	June 29, 1998	Fairbanks, Alaska	Balloon succeeded, mission unsuccessful
Klein/National Scientific Balloon Facility	Test Flight	July 18, 1998	Palestine, Texas	Successful
Ormes/Goddard Space Flight Center	Cosmic Ray Astrophysics	July 30, 1998	Lynn Lake, Canada	Successful
Richards/University of California, Berkeley	IR/Submillimeter Astrophysics	August 2, 1998	Palestine, Texas	Successful
Streitmatter/Goddard Space Flight Center	Cosmic Ray Astrophysics	August 4, 1998	Lynn Lake, Canada	Successful
Wilkins/Prairie View A&M University	Special Projects	August 18, 1998	Palestine, Texas	Successful
Bukiet/New Jersey Institute of Technology	Special Projects	August 21, 1998	Wallops Flight Facility	Successful
Pierce/Virginia Space Grant Consortium	Special Projects	August 22, 1998	Wallops Flight Facility	Successful
Tucker/Brown University	IR/Submillimeter Astrophysics	August 25, 1998	Palestine, Texas	Successful
Evenson/University of Delaware	Cosmic Ray Astrophysics	August 30, 1998	Lynn Lake, Canada	Successful
Klein, Silverberg/National Scientific Balloon Facility, NASA Goddard Space Flight Center	Test Flight	September 28, 1998	Fort Sumner, New Mexico	Successful

Table 4–63. NASA Balloon Flights (1989–1998[a]) (Continued)

Experimenter/Organization	**Discipline**	**Date**	**Site**	**Results**
Raque/Wallops Flight Facility	Test Flight	October 13, 1998	Fort Sumner, New Mexico	Successful
Raque/Wallops Flight Facility	Test Flight	October 15, 1998	Fort Sumner, New Mexico	Successful
Lange/California Institute of Technology	IR/Submillimeter Astrophysics	December 29, 1998	Antarctica	Successful

[a] "NASA Research Carriers Program Sounding Rocket and Balloon Projects Schedule," Copy provided by Keith Koehler, NASA Wallops Flight Facility Public Affairs Office.

Table 4–64. Magellan Mission Events[a]

Date	Event
May 4, 1989	Launch.
August 10, 1990	Venus orbit insertion and spacecraft checkout.
September 15, 1990–May 14, 1991	First mapping cycle: Radar mapping; Mapped 84 percent of the surface of the planet, with resolution 10 times better than achieved by the earlier Soviet Venera 15 and 16 missions.
May 15, 1991	Extended mission begins.[b]
May 15, 1991–January 14, 1992	Cycle 2: Imaged the south pole region and gaps from Cycle 1.
January 15, 1992–September 13, 1992	Cycle 3: Filled remaining gaps and collected stereo imagery; brought mapping coverage to 98 percent of the planet, with a resolution of approximately 100 m.
September 14, 1992–May 23, 1993	Cycle 4: Obtained gravity data by pointing the Magellan antenna toward Earth and measuring the Doppler shift in radio transmissions. These measurements were used to estimate variations in the gravitational field of Venus.
May 24, 1993–August 2, 1993	Aerobraking to circularize orbit and global gravity measurements.
August 3, 1993–August 29, 1994	Cycle 5: Gravity data acquisition using circularized orbit.
September 1994	Cycle 6: Collected high-resolution gravity data and conducted radio science experiments. Windmill experiment: Observed behavior of molecules in upper atmosphere.
October 11, 1994	Descent into Venus atmosphere.
October 12, 1994	Radio signal lost.

[a] "Magellan Mission to Venus," *http://nssdc.gsfc.nasa.gov/planetary/magellan.html* (accessed September 16, 2005). Also "Magellan Mission at a Glance," *http://www2.jpl.nasa.gov/magellan/fact.html* (accessed August 16, 2005). "Magellan: Mission Plan," *http://nssdc.gsfc.nasa.gov/planetary/mgncycles.html* (accessed September 19, 2005).

[b] There is some inconsistency about when the extended mission began. Most often, it is considered to have begun after the first mapping cycle. However, according to the former project manager, Douglas Griffith, Cycles 1–4 were funded by prime mission funding while Cycles 5 and 6 were funded by additional funding. He considers the extended mission to begin with Cycle 5. (E-mails from Douglas Griffith and Ron Baalke, September 19, 2005).

Table 4–65. Magellan Mission Characteristics

Launch Date/Launch Site	May 4, 1989/Cape Canaveral
Date of Reentry	Burned up in Venus's atmosphere October 12, 1994.
Launch Vehicle	STS-30/*Atlantis*
NASA Role	Mission management, operations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives[a]	Program objective: • To place a satellite carrying a radar sensor into orbit around Venus to obtain scientific data regarding the surface of Venus, to reduce and analyze these data, and to make the results available to the public and the scientific community. Mission objectives: • To obtain near global (greater than 70 percent coverage) radar images of the planet's surface, with resolution equivalent to optical imaging of 1 km (0.62 mi) per line pair. • To obtain a near global topographic map with 50-km (31-mi) spatial and 100-m (328-ft) vertical resolution. • To obtain near global (greater than 76 percent) gravity field data with 700-km (435-mi) or better resolution and 2 milligals to 3 milligals accuracy. • To develop an understanding of the geological evolution of the planet, principally its density distribution and dynamics.
Orbit Characteristics (around Venus):	
Apogee	8,029 km (4,990 mi)
Perigee	250 km (155 mi)
Inclination (deg)	86
Period (min)	195 (first cycle), 94 (fifth cycle)
Weight	Spacecraft: 3,449 kg (7,603 lb) at time of injection into Venus transfer orbit Radar sensor: 126 kg (278 lb)
Dimensions	Spacecraft: length: 6.4 m (21 ft), diameter: 4.6 m (15.1 ft); parabolic dish antenna: 3.6 m (11.8 ft); solar panels spanned 9.2 m (30.2 ft); total area of solar panels: 12.6 sq m (135.6 sq ft)
Shape	Bus: 10-sided
Power Source	Solar panels and nickel cadmium batteries
Prime Contractor	Spacecraft: Martin Marietta Astronautics Group; radar sensor: Hughes Aircraft Co.
PIs	Radar: Gordon Pettengill, Massachusetts Institute of Technology Gravity: William Sjogren, Jet Propulsion Laboratory; and Georges Balmino, France[b]

Table 4–65. Magellan Mission Characteristics (Continued)

Instruments and Experiments	The radar system consisted of the radar sensor, high-gain antenna, and altimeter antenna. The radar sensor operated as a SAR at 2,385-GHz frequency in the S-band. The high-gain antenna transmitted and received active radar pulses for the SAR mode and collected microwave energy passively emitted by Venus for the radiometer mode. In the SAR mode, the images had a radar resolution better than 270 m (886 ft) with a minimum of four incoherent looks (to reduce speckle) over an altitude range from 250 km to 2,100 km (155 mi to 1,305 mi). When the radar system operated as a passive radiometer, the temperature resolution was 2 K. As an altimeter, the radar used a separate fan beam antenna pointed vertically at the planet's surface to measure the heights of geologic features. Magellan altimetry had a vertical resolution of less than 30 m (98 ft) with a spot size of 20 km to 55 km (12 mi to 34 mi). In addition to the antennae, the radar system consisted of a single box of flight hardware containing a stable local oscillator; pulse repetition frequency/timing; range dispersion; transmitter; output network; receiver; baseband processor; data formatter; and telemetry and command. Each unit was duplicated to provide redundancy that could be switched by ground command.[c]
Results[d]	Magellan mapped 98 percent of the planet's surface with radar and compiled a high-resolution gravity map of 95 percent of the planet. Key scientific findings included the following: • Evidence relating to the role of impacts, volcanism, and tectonism in the formation of Venusian surface structures. • Discovery that the surface of Venus was covered largely by volcanic materials. Volcanic surface features, such as vast lava plains, fields of small lava domes, and large shield volcanoes were common. • There were few impact craters, suggesting that the surface was, in general, geologically young—less than 800 million years old. • The presence of lava channels more than 6,000 km (3,728 mi) long suggested river-like flows of extremely low-viscosity lava that probably erupted at a high rate. • Large pancake-shaped volcanic domes suggested the presence of a type of lava produced by extensive evolution of crustal rocks.

Table 4–65. Magellan Mission Characteristics (Continued)

Results	• The typical signs of terrestrial plate tectonics—continental drift and basin floor spreading—were not in evidence on Venus. The planet's tectonics were dominated by a system of global rift zones and numerous broad, low domical structures called coronae, which were produced by the upwelling and subsidence of magma from the mantle. • Although Venus had a dense atmosphere, the surface revealed no evidence of substantial wind erosion; it revealed evidence of limited wind transport of dust and sand only. This contrasted with Mars, where there was a thin atmosphere but substantial evidence of wind erosion and transport of dust and sand.

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[a] "Magellan Mission Operations Report," Report no. E-844-89-30-01, NASA Office of Space Science and Applications, p. viii. (NASA History Office Electronic Document 30712).

[b] "Magellan Fact Sheet," *http://nssdc.gsfc.nasa.gov/planetary/factsheet.html* (accessed October 12, 2005).

[c] "Magellan Mission Operations Report," Report no. E-844-89-30-01, NASA Office of Space Science and Applications (NASA History Office Electronic Document 30712).

[d] "Magellan Fact Sheet," *http://nssdc.gsfc.nasa.gov/planetary/factsheet.html* (accessed October 12, 2005).

Table 4–66. Galileo Major Mission Events (1989–1999)

Date	Event
October 18, 1989	Launch from Kennedy Space Center on Space Shuttle *Atlantis*, STS-34
October 1989–December 1997	Primary mission
February 10, 1990	Venus flyby, at altitude of 16,000 km (10,000 mi)
December 8, 1990	First Earth flyby, at altitude of 960 km (597 mi)
April 11, 1991	Galileo unsuccessfully attempts to unfurl its high gain antenna
October 29, 1991	Asteroid Gaspra flyby, at 1,601 km (1,000 mi)
December 8, 1992	Second Earth flyby, at altitude of 303 km (188 mi), end of VEEGA phase
August 28, 1993	Asteroid Ida flyby, at 2,400 km (1,400 mi)
July 16–July 22, 1994	Comet Shoemaker-Levy 9, observed impacts of comet fragments into Jupiter
July 13, 1995	Atmospheric probe released
July 27, 1995	First sustained firing of Galileo main rocket engine
November 26, 1995	Orbiter enters Jupiter's environment, crossing from interplanetary space into its magnetosphere
December 7, 1995	Probe enters Jupiter's atmosphere; relays data for 58 minutes
December 7, 1995	Orbiter arrives at Jupiter, passes Europa and Io, fires main engine to brake into Jupiter's orbit
December 7, 1995–December 7, 1997	Prime mission orbital tour, 11 orbits
March 1996	Engineers radio new software to Galileo permitting data compression for low gain antenna transmission
September 6, 1996	Closest approach, 261 km (162 mi), to Ganymede
December 7, 1997	Completed primary mission
December 8, 1997–December 31, 1999	Galileo Europa Mission (GEM)
December 16, 1997–May 4, 1999	Europa campaign, eight orbits
December 16, 1997	Closest approach, 201 km (125 mi), to Europa
May 5, 1999–October 10, 1999	Jupiter water/Io torus study
October 11, 1999–December 31, 1999	Io campaign

Table 4–67. Galileo Encounters at Jupiter (1995–1999[a])

Orbit	Target	Date	Altitude
0	Io	December 7, 1995	897 km (558 mi)
G1	Ganymede	June 27, 1996	835 km (519 mi)
G2	Ganymede	September 6, 1996	261 km (162 mi)
C3	Callisto	November 4, 1996	1,136 km (706 mi)
E4	Europa	December 19, 1996	692 km (430 mi)
5	None		
E6	Europa	February 20, 1997	586 km (364 mi)
G7	Ganymede	April 5, 1997	3,102 km (1,928 mi)
G8	Ganymede	May 7, 1997	1,603 km (996 mi)
C9	Callisto	June 25, 1997	418 km (260 mi)
C10	Callisto	September 17, 1997	535 km (333 mi)
E11	Europa	November 6, 1997	2,043 km (1,270 mi)
E12[b]	Europa	December 16, 1997	201 km (125 mi)
13	None		
E14	Europa	March 29, 1998	1,644 km (1,022 mi)
E15	Europa	May 31, 1998	2,515 km (1,562 mi)
E16	Europa	July 21, 1998	1,834 km (1,140 mi)
E17	Europa	September 26, 1998	3,582 km (2,226 mi)
E18	Europa	November 22, 1998	2,271 km (1,411 mi)
E19	Europa	February 1, 1999	1,439 km (894 mi)
C20	Callisto	May 5, 1999	1,321 km (821 mi)
C21	Callisto	June 30, 1999	1,048 km (651 mi)
C22	Callisto	August 14, 1999	2,299 km (1,429 mi)
C23	Callisto	September 16, 1999	1,052 km (654 mi)
I24	Io	October 11, 1999	611 km (380 mi)
I25	Io	November 26, 1999	301 km (187 mi)

[a] "Galileo End of Mission Press Kit," p. 10.

[b] Beginning of Galileo Europa Mission (GEM).

Table 4–68. Galileo Mission Characteristics

Launch Date/Launch Site	October 18, 1989/Kennedy Space Center
Date of Reentry	No reentry. Mission ended on September 21, 2003, when the spacecraft passed into Jupiter's shadow and disintegrated.
Launch Vehicle	STS-34/*Atlantis*
NASA Role	Project management; designing, building, testing, operating, and tracking the spacecraft and probe
Responsible (Lead) Center	Jet Propulsion Laboratory: Mission operations, design and development of orbiter; Ames Research Center: Developed probe
Mission Objectives	Primary objectives: • Deliver an entry probe to make *in situ* measurements of the atmosphere of Jupiter and to place an orbiter around Jupiter with the ability to provide imaging, remote sensing, and magnetospheric investigation of Jupiter and its satellites during nearly two years of orbital operations. Secondary goals: • Collect Venus science and Earth-Moon imaging data, available during the VEEGA portion of the trajectory. • Obtain asteroid images during passages through the asteroid belt. • During the planetary cruise phase, obtain gravity wave detection and measurements of the interplanetary medium, solar magnetic field, and solar wind structure. Science objectives: • Investigate the chemical composition and physical state of Jupiter's atmosphere. • Characterize the morphology, physical state, and dynamic properties of the Jovian satellites. • Analyze the structure and physical dynamics of the Jovian magnetosphere.
Orbit/Trajectory Characteristics	VEEGA trajectory using gravity assist maneuvers with Venus and Earth; varying orbits around Jupiter and Jupiter's moons.
Weight[a]	Orbiter: 2,223 kg (4,902 lbs), at launch; included a 118-kg (260-lb) science payload and 925 kg (2,040 lb) of propellant Probe: 339 kg (750 lb) total
Dimensions[b]	Orbiter: 5.3 m (17 ft) high; magnetometer boom extended 11 m (36 ft) to one side Probe: 127 cm (50 in) diameter, 91 cm (36 in) high
Power Source	Radioisotope thermoelectric generators
Prime Contractor	Jet Propulsion Laboratory (orbiter), Hughes Aircraft Company (probe)

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments	Probe: • ASI PI: Alvin Seiff, Ames Research Center The ASI provided information about temperature, density, pressure, and molecular weight of atmospheric gases. These quantities were determined from the measured deceleration of the Probe during the atmospheric entry phase. During the parachute-descent phase, temperature and pressure were measured directly by sensors extending from the body of the spacecraft. • NMS PI: Hasso Niemann, Goddard Space Flight Center The NMS analyzed the chemical composition of gases by measuring their molecular weights. • HAD PI: Ulf von Zahn, Bonn University, Germany The HAD determined the ratio of hydrogen to helium in Jupiter's atmosphere. This instrument accurately measured the refractive index of Jovian air to precisely determine the helium abundance. • NEP PI: Boris Ragent, Ames Research Center The NEP located and measured cloud particles in the immediate vicinity of the Galileo Probe. This instrument used measurements of scattered light from a laser beam directed at an arm extending from the Probe to detect and study cloud particles. • NFR PI: Larry Sromovsky, University of Wisconsin The NFR sensed the differences between the flux of light and heat radiated downward and upward at various levels in Jupiter's atmosphere. Such measurements could provide information on the location of cloud layers and power sources for atmospheric winds. This instrument used an array of rotating detectors capable of sensing small variations in visible and infrared radiation fluxes. • LRD PI: Louis Lanzerotti, Bell Laboratories The LRD was used together with the scaling, data processing, and data formatting of the EPI. The LRD and EPI shared the electrical system collecting the LRD data. The LRD searched and recorded radio bursts and optical flashes generated by lightning in Jupiter's atmosphere. These measurements were made using an optical sensor and radio receiver on the Probe.

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments	• EPI PI: Louis Lanzerotti, Bell Laboratories The EPI was used before entry to measure fluxes of electrons, protons, alpha particles, and heavy ions as the Probe passes through the innermost regions of Jupiter's magnetosphere and ionosphere. • Doppler Wind Experiment This experiment used variations in the frequency of the radio signal from the Probe to derive variation of wind speed with altitude in Jupiter's atmosphere. Orbiter (Despun Platform): • Solid-State Imaging (SSI) Camera Team Leader: Michael J. S. Belton, National Optical Astronomy Observatories The 1,500-mm (59-in)-focal length telescopic camera system obtained images of Jupiter's satellites in visible light at resolutions 20 to 1,000 times better than Voyager's best, largely because it flew closer to the satellites. The CCD sensor of 800 pixels by 800 pixels was more sensitive and had a broader color detection band than the vidicons of Voyager. • Near-Infrared Mapping Spectrometer (NIMS) PI: Robert Carlson, Jet Propulsion Laboratory The NIMS measured the surface and atmospheric thermal, compositional, and structural nature of the Galilean satellites. • UVS PI: Charles Hord, University of Colorado The investigation included the UVS on the despun platform and the Extreme Ultraviolet Spectrometer (EUVS) on the spun section. The investigation determined the loss rates of volatile gases from the Galilean satellites and studied the composition and structure of the upper Jovian atmosphere, including atmospheric gases, aerosols, etc. The investigation also examined the physical processes occurring in the Io plasma torus. The EUVS was a modified flight spare of the Voyager UVS. • Photopolarimeter Radiometer (PPR) PI: James E. Hansen, Goddard Institute for Space Studies The PPR observed light in the visible and infrared wavelengths and provided data on atmospheric composition and thermal/reflected energy distribution and radiation.

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments	Orbiter (Spinning Spacecraft Section) • MAG PI: Margaret G. Kivelson, University of California, Los Angeles The MAG sensed strength and fluctuations of magnetic fields in the spacecraft's immediate environment. The magnetometer sensors were mounted on an 11-meter (36-foot) boom to minimize interference from the spacecraft. • EUVS PI: Charles Hord, University of Colorado The EUVS determined loss rates of volatile gases from the Galilean satellites and studied the composition and structure of the upper Jovian atmosphere. As Galileo spun, the EUVS observed a narrow ribbon of space perpendicular to the spin axis. • Energetic Particles Detector (EPD) PI: D. J. Williams, The Johns Hopkins University, Applied Physics Laboratory The EPD measured the energy, composition, intensity, and angular distribution of electrons, protons, and heavy ions in the spacecraft's immediate environment. • Plasma Investigation Subsystem (PLS) PI: Lou Frank, University of Iowa In the spacecraft's immediate environment, the PLS detected and measured low-energy charged particles (ions), as well as their composition; energy; temperature density; and three-dimensional distribution and bulk motions. • Plasma Wave Subsystem (PWS) PI: Donald A. Gurnett, University of Iowa This instrument studied waves generated by charged particles. The instrument measured the electrostatic and electromagnetic components of waves and wave-particle interactions in three dimensions. • Dust Detector Subsystem (DDS) PI: Eberhard Grun, Max-Planck-Institute für Kernphysik, Germany This instrument determined the mass, velocity, charge, and flight direction of submicron particles in interplanetary space and the Jovian system. • Heavy Ion Counter (HIC) (engineering experiment) PI: Edward Stone, Jet Propulsion Laboratory, California Institute of Technology This experiment assessed the potentially hazardous charged-particle environments that the spacecraft flew through. The experiment provided data on collisions with ionized sulfur and oxygen atoms trapped in the Jovian magnetic field.

Table 4–68. Galileo Mission Characteristics (Continued)

Instruments and Experiments[c]	• Radio Science: Celestial Mechanics Team Leader: John Anderson, Celestial Mechanics Jet Propulsion Laboratory This instrument determined masses and internal structures and motions of bodies from spacecraft tracking. • Radio Science: Propagation Team Leader: H. Taylor Howard, Stanford University This instrument determined satellite radii and atmospheric structure from radio propagation. Interdisciplinary Investigators • Frances Bagenal, University of Colorado • Andrew F. Cheng, The Johns Hopkins University • Fraser P. Fanale, University of Hawaii • Peter Gierasch, Cornell University • Donald M. Hunten, University of Arizona • Andrew P. Ingersoll, California Institute of Technology • Wing-Huen Ip, NSPO/RDD, Taipei • Michael McElroy, Harvard University • David Morrison, Ames Research Center • Glenn S. Orton, Jet Propulsion Laboratory • Tobias Owen, State University of New York • Alain Roux, Centre de Recherches en Physique de l'Environment • Christopher T. Russell, University of California at Los Angeles • Carl Sagan, Cornell University • Gerald Schubert, University of California at Los Angeles • William H. Smyth, Atmospheric & Environmental Research, Inc. • James Van Allen, University of Iowa
Results	The Galileo mission accomplished more than 70 percent of its science mission objectives. A significant finding, the discovery of a frozen ocean of water covering Europa, led to speculation about the possibility of life on the moon. The discovery of "warm ice" or possibly liquid water, and later cracks where warm water "environmental niches" might exist as well as icebergs, raised questions prompting scientists to call for another mission to Europa.[d] See additional results in the mission narrative above.

Table 4–68. Galileo Mission Characteristics (Continued)

Remarks	Galileo accomplished the following "firsts":[e] • First mission to make a close flyby of an asteroid (Gaspra) • First mission to discover a satellite of an asteroid (Ida's satellite Dactyl) • First multispectral study of the moon • First atmospheric probe to enter Jupiter's atmosphere • First spacecraft to go into orbit around Jupiter • First direct observations of a comet impacting a planet (Shoemaker-Levy 9)

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[a] "Galileo End of Mission Press Kit." Galileo press contact representative cited end-of-mission press kit as most reliable. "Galileo Mission Operation Report," "Galileo Jupiter Arrival Press Kit," and JPL Galileo Web site all have different figures for size and weight.

[b] "Galileo End of Mission Press Kit."

[c] "Galileo's Science Instruments," *http://www2.jpl.nasa.gov/galileo/instruments/* (accessed August 18, 2005). Also "The Galileo Probe Spacecraft," *http://spaceprojects.arc.nasa.gov/Space_Projects/galileo_probe/htmls/probe_spacecraft.html* (accessed May 4, 2006). "Galileo Jupiter Arrival Press Kit," December 1995, pp. 38–40, *http://www.jpl.nasa.gov/news/press_kits/gllarpk.pdf* (accessed September 12, 2005).

[d] Roger D. Launius in Siddiqi, p. 8.

[e] "Galileo Project Information," *http://nssdc.gsfc.nasa.gov/planetary/galileo.html* (accessed September 17, 2005).

Table 4–69. Discovery Missions Approved by NASA, 1993–1998[a]

Mission	Selection Year	Launch Date	Mission Description
NEAR	1993	February 1996	The first spacecraft to orbit and study an asteroid
Mars Pathfinder	1993	December 1996	Demonstrated a less costly method of landing a spacecraft and science instruments on Mars using a small rover to explore Martian terrain
Lunar Prospector	1994	January 1998	Offered insight on the Moon's origin and evolution; also sought to determine whether water ice existed at the Moon's poles
Stardust	1995	February 1999	The first spacecraft to collect comet and interstellar dust particles and return them to Earth
CONTOUR	1997	July 2002	To encounter and study at least three comets
Genesis	1997	August 2001	Collected wind particles to improve understanding of the evolution of the solar system

[a] Snyder, "NASA and Planetary Exploration," in Logsdon, ed., *Exploring the Unknown: Selected Documents in the History of the U.S. Civil Space Program, Volume V,* p. 296.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics

Launch Date/Launch Site	February 17, 1996/Cape Canaveral
Date of Reentry	Communication with spacecraft ended February 28, 2001.
Launch Vehicle	Delta II 7925
NASA Role	Instrument team leaders; provided magnetometer
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives	Mission objectives:[a] • Place a satellite carrying multiple scientific instruments into orbit around the near-Earth asteroid 433 Eros. • Carry out quantitative and comprehensive measurements for one year of the asteroid's composition and structure. • Reduce and analyze these data. • Make the results available to the scientific community and the public. Science objectives:[b] • Characterize the physical and geological properties of a near-Earth asteroid and infer its elemental and mineralogical composition. • Clarify relationships between asteroids, comets, and meteorites. • Further understand the processes and conditions during the formation and early evolution of the planets.
Orbit Characteristics	Interplanetary trajectory
Weight	805 kg (1,775 lb)
Dimensions	Eight 18 sq ft (1.75 sq m) panels; height: 9.2 ft (2.8 m) from bottom of spacecraft to top of its main antenna; solar panels: 6 ft by 4 ft (1.8 m by 1.2 m); main dish antenna: 5 ft (1.5 m) diameter
Shape	Octagonal
Power Source	Solar cells
Prime Contractor	The Johns Hopkins University Applied Physics Laboratory
Instruments and Experiments	• Multispectral Imager (MSI) Team Leader: Joseph Veverka, Cornell University The MSI imaged Eros in multiple spectral bands to determine its size, shape, and spin characteristics to map mineral distributions and provide data for optical navigation. The MSI was equipped with a 537-pixel by 224-pixel CCD imaging detector with five-element, radiation-hard refractive optics capable of photographing details on Eros' surface as small as 10 ft (3 m) in diameter.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Instruments and Experiments	Adapted by the APL from a military remote sensing system, the instrument covered the spectral range from 0.4 microns to 1.1 microns. The instrument had an eight-position filter wheel with filters chosen to optimize sensitivity to minerals expected to occur on Eros. The MSI had a FOV of 2.26 degrees by 2.95 degrees and a pixel resolution corresponding to 31 ft by 53 ft (9.6 m by 16.2 m) from 62 mi (100 km). • MAG Team Leader: Mario H. Acuña, Goddard Space Flight Center The three-axis fluxgate magnetometer could measure the asteroid's magnetic field from dc to 10 Hz. The sensor head was mounted on the HGA feed, while the electronics were mounted on the spacecraft top deck. The sensor, supplied by NASA and the Goddard Space Flight Center, had eight selectable sensitivity levels. The MAG was used to search for and map any intrinsic magnetic field around Eros. • Near Infrared Spectrometer (NIS) Team Leader: Joseph Veverka, Cornell University The NIS mapped the distribution and abundance of surface minerals like olivine and pyroxene by measuring reflected sunlight in the near-infrared range from 0.8 micrometer to 2.7 micrometers in 64 channels. With the measurements of elemental composition from the X-Ray/Gamma-Ray Spectrometer (XGRS) and color imagery from the MSI, the NIS provided a link between asteroids and meteorites and clarified the processes by which asteroids formed and evolved. The NIS, adapted from a military remote sensing instrument, was a grating spectrometer dispersing light from the slit FOV across a pair of passively cooled, one-dimensional array detectors. One detector was a germanium array covering the lower wavelengths from 0.8 micron to 1.5 microns; the other was an indium-gallium-arsenide array covering 1.3 microns to 2.7 microns. Mirror scanning combined with spacecraft motion was used to build up hyperspectral images. The NIS also carried a diffuse gold calibration target that reflected sunlight into the spectrometer and provided in-flight spectral calibration.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Instruments and Experiments	• XGRS Team Leader: Jacob I. Trombka, Goddard Space Flight Center The XGRS consisted of two state-of-the-art sensors: an x-ray spectrometer and a gamma-ray spectrometer. It measured and mapped abundances of several dozen key elements at and near the surface of Eros. The x-ray spectrometer (XRS) detected the characteristic x-ray line emissions excited by solar x-rays from major elements in the asteroid surface. The XRS covered the energy range from 1 keV to 10 keV using three gas-proportional counters. The balanced, differential filter technique was used to separate the closely spaced magnesium, aluminum, and silicon lines below 2 keV. The gas-proportional counters directly resolved higher energy line emissions from calcium and iron. A mechanical collimator gave the XRS a 5-degree FOV to map the chemical composition at spatial resolutions as low as 1.2 mi (2 km). The XRS included a separate solar monitor system to continuously measure the incident spectrum of solar x-rays. In-flight calibration capability also was provided. The gamma-ray spectrometer (GRS) detected characteristic gamma rays in the range from 0.3-MeV to 10-MeV; the gamma rays emitted from specific elements in the surface such as potassium, silicon, and iron. The GRS used a body-mounted, passively cooled sodium iodide detector enveloped by an active bismuth germanate anti-coincidence shield to provide a 45-degree FOV.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Instruments and Experiments[c]	• NEAR Laser Rangefinder (NLR) Team Leader: Maria T. Zuber, Massachusetts Institute of Technology/Goddard Space Flight Center The NLR was a laser altimeter measuring the distance from the spacecraft to the asteroid surface to build up high-resolution topographic profiles. The NLR sent short bursts of laser light to the surface and then recorded the time required for the signal to return from the asteroid. It sent a small portion of each emitted laser pulse through an optical fiber of known length and a small portion of each pulse into the receiver, providing continuous in-flight calibration of the timing circuit. The ranging data was used to construct a global shape model and a global topographic map of Eros with horizontal resolution of about 1,000 ft (300 m). The NLR also measured detailed topographic profiles of surface features on Eros with a best spatial resolution of about 12 ft (4 m). The profiles were used as constraints on models of the origin and evolution of surface features. • Radio Science Experiment Team Leader: Donald K. Yeomans, Jet Propulsion Laboratory The radio science experiment consisted of a coherent X-band transponder measuring the radial velocities of the spacecraft relative to Earth, thus allowing the asteroid's gravity field to be mapped. It used the NEAR radio tracking system to determine the mass and mass distribution of the asteroid. Measurements were made of the two-way Doppler shift in radio frequency between the spacecraft and Earth to an accuracy of better than 0.025 in/sec (0.1 mm/sec). These measurements were used to determine line-of-sight velocity variations induced in the spacecraft's motion by the changing gravitational effects produced by the neighboring asteroid. Combined with data from other NEAR instruments, this information allowed accurate modeling of Eros' density and mass distribution.

Table 4–70. Near Earth Asteroid Rendezvous Mission Characteristics (Continued)

Results	The NEAR mission science instruments observed about two-thirds of Eros on December 23, 1998, during a flyby past the asteroid. The NEAR mission discovered that Eros was smaller than expected and that the asteroid had two medium-sized craters, a long surface ridge, and a density similar to the density of Earth's crust. The NEAR mission also discovered that Eros had two medium-sized craters, a long surface ridge, and a density similar to that of Earth's crust.[d]

[a] "Near Earth Asteroid Rendezvous Pre-Launch Mission Operation Report," February 2, 1996, p. 4 (NASA History Office Folder 31049).

[b] "The Near Earth Asteroid Rendezvous; A Guide to the Mission, the Spacecraft, and the People," p. 7, *http://near.jhuapl.edu/media/99-1030B_NEARMarch.pdf* (accessed May 4, 2006).

[c] "The Near Earth Asteroid Rendezvous; A Guide to the Mission, the Spacecraft, and the People," pp. 15–17.

[d] Most NEAR discoveries were made after 1998, after the period covered in this volume.

Table 4–71. Lunar Prospector Mission Characteristics

Launch Date/Launch Site	January 6, 1998/Kennedy Space Center
Date of Reentry	Impacted on Moon July 31, 1999.
Launch Vehicle	Athena II
NASA Role	Mission management
Responsible (Lead) Center	Ames Research Center
Mission/Science Objectives	Science objectives: • "Prospect" the lunar crust and atmosphere for potential resources, including minerals, water ice, and certain gases. • Map the Moon's gravitational and magnetic fields. • Learn more about the size and content of the Moon's core.
Orbit Characteristics:	
Apogee	Initial orbit: 63 mi (100 km) around Moon; lowered after one year to obtain detailed measurements Final orbit: ~18 mi (30 km)
Perigee	Initial orbit: 63 mi (100 km) around Moon Final orbit: ~18 mi (30 km)
Inclination (deg)	89.2 (polar)
Period (min)	118 min (100-km orbit), 112 min (40 km-orbit), 111 min (30-km orbit)
Weight	295 kg (650 lb) (fueled)
Dimensions	1.4 m by 1.2 m (4.6 ft by 4 ft)
Shape	Cylindrical drum
Power Source	Solar cells and nickel cadmium battery
Prime Contractor	Lockheed Martin
Instruments and Experiments	• Neutron Spectrometer (NS): PI: William Feldman, Los Alamos National Laboratory The NS searched for water by indirectly detecting hydrogen on the Moon's surface. Located 63 mi (100 km) above the Moon's surface, the NS did not detect hydrogen directly. Instead, it looked for "cool" neutrons—neutrons that have bounced off a hydrogen atom somewhere on the lunar surface. The NS weighed 8.5 lb (3.9 kg), consumed 2.5 W of power, and produced 49 bps. It was deployed together with the APS. This was the first use of neutron spectroscopy for planetary science.

Table 4–71. Lunar Prospector Mission Characteristics (Continued)

Instruments and Experiments	• GRS PI: G. Scott Hubbard, Ames Research Center The GRS mapped abundances of 10 elements on the Moon's surface: thorium, potassium, uranium, iron, oxygen, silicon, aluminum, calcium, magnesium, and titanium. The GRS was especially sensitive to the heavy, radioactive element thorium and the light element potassium. These were particularly plentiful in the Moon's youngest rocks, the last part of the crust to solidify. This mapping provided information on the composition of the surface layer and the Moon's origin and evolution. The GRS weighed 19 lb (8.6 kg), used 3 W of power, and produced data at a rate of 688 bps. It was deployed on one of the Lunar Prospector's three booms. • Alpha Particle Spectrometer (APS) PI: Alan Binder, Lockheed Martin The APS detected alpha particles emitted by radioactive gases, such as radon and polonium, leaking out of the lunar interior. The APS detected outgassing events to determine their frequency and location. Outgassing suggested volcanic and tectonic events indicating the activity level of the Moon. The APS weighed 9 lb (4 kg), consumed 7 W of power and produced data at a rate of 181 bps. • MAG and Electron Reflectometer (ER) PI (MAG): Mario Acuña, Goddard Space Flight Center; Lon Hood, University of Arizona PI (ER): Robert Lin, University of California Berkeley The MAG and ER mapped lunar magnetic fields and provided information on the size and characteristics of the Moon's inner core. The instruments were copies of detectors on board the Mars Global Surveyor spacecraft, launched in December 1996, with some modifications to adapt them for a spinning spacecraft. The magnetic fields measured by the MAG were a combination of Earth's magnetic field, the field carried from the Sun by the solar wind, and the Moon's field, which is extremely weak compared to that of Earth. The MAG was mounted on a boom 8.5 ft (2.6 m) from the spacecraft to isolate it from the magnetic fields generated by the spacecraft's own electronics.

Table 4–71. Lunar Prospector Mission Characteristics (Continued)

Instruments and Experiments[a]	The ER, a remote instrument, measured the magnetic field at the surface of the Moon. Together with the MAG, the two instruments detected local variations in the Moon's magnetic field arising from selenological features on the lunar surface. The ER was linked to the MAG by a smaller 2.5-ft (0.8-m) boom. The combined weight of the MAG and ER was approximately 11 lb (5 kg). Together, the two instruments used 4.5 w of power, and produced 670 bps of data. • Doppler Gravity Experiment (DGE) PI: Alex Konopliv, NASA Jet Propulsion Laboratory The DGE mapped the global lunar gravity field and provided an enhanced model of the Moon's gravity known to be non-uniform as a result of mass concentrations (mascons) distributed below the Moon's surface. The newly derived operational lunar gravity map was used to perform monthly orbit adjustments needed to counteract the uneven gravity field of the Moon that degraded the orbit over time.
Results	NS data allowed mission scientists to establish the existence of significant concentrations of hydrogen at the lunar poles based on telltale dips in the epithermal neutron energy spectra sent back to Earth by the NS. If, as some scientists suspected, this excess hydrogen existed as part of frozen water molecules buried in permanently shadowed craters at the lunar poles, there could be as much as 260 million metric tons of water ice (75 billion gallons of water) on the Moon. The GRS acquired the first global measurements of gamma-ray spectra from the lunar surface. Since gamma rays coming from the lunar surface carry information about lunar elemental composition, this data set comprised the first direct elemental composition measurements made for the entire lunar surface.

Table 4–71. Lunar Prospector Mission Characteristics (Continued)

Results	By mission's end, the MAG and ER experiment obtained more than 700,000 electron reflection measurements distributed over the entire Moon. This was sufficient to map most of the lunar surface at 3-degree resolution and some regions at 0.5-degree (15-km) (9.3-mi) resolution. Measurements also showed systematic variations in magnetic field strength over the different mare units. The primary mission yielded 100-km (62-mi) altitude measurements of crustal magnetic fields over the entire surface. The MAG and ER measurements established that miniature magnetospheres were forming around concentrations of strong crustal magnetic fields occurring diametrically opposite specific impact basins. A remarkable property of these miniature magnetospheres was that they sometimes disappeared. Initial measurements of the lunar-induced magnetic dipole moment were obtained using magnetometer data when the Moon was in a lobe of the geomagnetic tail. These measurements were consistent with the presence of a metallic core with a radius between 250 km and 430 km (155 mi and 267 mi). This was compatible with independent evidence from gravity and laser ranging data, which suggested a ~300-km (186-mi)-radius core. The extended mission, with its lower altitude, provided the DGE with the means to generate an improved lunar gravity model, uncover additional mascons (mass concentrations), and further refine our understanding of the Moon's interior. The APS collected voluminous high-quality data throughout the primary mission and experienced more solar activity than predicted.[b]

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[a] "Introduction to Instruments," *http://lunar.arc.nasa.gov/results/instruments.htm* (accessed May 18, 2006).

[b] "Lunar Prospector, End of Mission & Overview," Press Kit, July 1999.

Table 4–72. Clementine Mission Characteristics

Launch Date/Launch Site	January 25, 1994/Vandenberg Air Force Base
Date of Reentry	No reentry. Mission ended June 1994.
Launch Vehicle	Titan IIG
NASA Role	Science team, use of DSN, lunar and asteroid navigation
Responsible (Lead) Center	Goddard Space Flight Center
Mission Objectives[a]	• To demonstrate advanced lightweight components and technologies under extended exposure to the space environment. • To collect data of interest to the international civilian scientific sector and to stimulate public interest in space exploration. Scientific goals: • To image the entire lunar surface and the asteroid 1620 Geographos during a close flyby,
Orbit Characteristics:	Lunar orbit
Apogee	4,594 km (2,855 mi)
Perigee	2,162 km (1,343 mi)
Inclination (deg)	90
Period (min)	300
Weight	424 kg (935 lb) (with propellant)
Dimensions	1.14 m (3.7 ft) diameter by 1.88 m (6.2 ft) length
Shape	Octagonal
Power Source	Solar panels and battery
Prime Contractor	National Research Laboratory, Lawrence Livermore
Principal Investigator	Eugene M. Shoemaker
Instruments and Experiments	• Charged Particle Telescope (CPT): Designed to measure the flux and spectra of energetic protons (3 MeV–80 MeV) and electrons (25 KeV–500 KeV). The primary goals of the investigation were the following: — Study the interaction of Earth's magnetotail and interplanetary shocks with the Moon. — Monitor the solar wind in regions far removed from other spacecraft as part of a multimission coordinated study. — Measure the effects of incident particles on the operating ability of the spacecraft solar cells and other sensors.

Table 4–72. Clementine Mission Characteristics (Continued)

Instruments and Experiments	• The single-element telescope had a 10-degree, half-angle FOV. The detector, a silicon surface-barrier type with an area of 100 sq mm (0.16 sq in) and a thickness of 3 mm (0.1 in), was shielded so as to prevent protons below 30 MeV from reaching it from directions other than via the aperture. The signal from the detector was broken up into nine channels, the lowest six dedicated to electron detection and the highest three to protons and heavier ions. • Ultraviolet/Visible CCD Camera (UV/Vis): The UV/Vis were designed to study the surfaces of the Moon and the asteroid Geographos at five different wavelengths in the UV and visible spectrum. This experiment yielded information on the petrologic properties of the surface material on the Moon, as well as giving images useful for morphologic studies and cratering statistics. The Geographos rendezvous was cancelled due to equipment malfunction. • Near-Infrared (NIR) CCD Camera: This experiment was designed to study the surfaces of the Moon and the near-Earth asteroid 1620 Geographos at six different wavelengths in the near-infrared spectrum. This experiment yielded information on the petrology of the surface material on the Moon. The rendezvous with Geographos was cancelled due to equipment malfunction. • Long-Wavelength Infrared (LWIR) Camera: This camera was designed to image darkside features on both the Moon and the near-Earth asteroid 1620 Geographos in the thermal infrared spectrum and to allow measurement of thermal properties of material on both bodies, from which an assessment of regolith characteristics could be made. The Geographos phase of the mission was cancelled due to equipment malfunction. • Laser Image Detection and Ranging (LIDAR) System: This system was designed to measure the distance from the spacecraft to a point on the surface of the Moon, allowing an altimetric map to be made. The experiment also was designed to measure distances to the surface of Geographos, but this mission phase was cancelled.

Table 4–72. Clementine Mission Characteristics (Continued)

Instruments and Experiments	• High-Resolution Camera: This camera consisted of a telescope with an image intensifier and a frame-transfer CCD imager. The imaging system was designed to study selected portions of the surfaces of the Moon and the near-Earth asteroid 1620 Geographos, although the asteroid rendezvous was cancelled. This experiment allowed detailed study of surface processes on the Moon and, combined with spectral data, allowed high-resolution compositional and geologic studies. • Star Tracker Cameras (2): Each camera consisted of a knife-edge baffle vane and a lens mounted to the CCD camera housing. Both cameras were located at one end of the spacecraft near the main thruster. The main purpose of the star tracker cameras was to image the background stars to provide attitude determination for the spacecraft. This was done by comparing stellar images to an on–board star catalog to establish absolute angular references for navigation. Images of Earth and the Moon for scientific purposes could also be obtained. • S-Band Transponder Doppler Gravity Experiment: This experiment used measurements of perturbations in the motion of the spacecraft to infer the lunar gravity field. Clementine was equipped with an S-band microwave transponder and two S-band omnidirectional high-rate antennae used for tracking by the Naval Research Laboratory tracking station in Pomonkey, Maryland and the NASA DSN. The calculated lunar gravity field could be used to model subsurface lunar structure. The Pomonkey station measured velocity to an accuracy of 3 mm/s (0.1 in/s), while the DSN stations achieved about 0.3 mm/s (0.01 in s). More than 361,000 observations were made, approximately 57,000 at less than 1,000-km (621-mi) altitude. • Bistatic Radar Experiment: This experiment used the radio transmitting equipment aboard Clementine to search the Moon's polar regions for evidence of ice in permanently shadowed craters. The basic method of bistatic radar involved a spacecraft transmitting a radio signal at a point on the target body. Reflections of these signals from the target were received on Earth. Properties of the received reflections could be interpreted to give information on the target surface.

Table 4–72. Clementine Mission Characteristics (Continued)

Results	• Produced first global digital map of the Moon. • Found water ice at lunar pole (later disproved). • After leaving lunar orbit, a malfunction in one of the on-board computers on May 7, 1994, caused a thruster to fire until it had used up all its fuel, leaving the spacecraft spinning at about 80 revolutions per minute with no spin control. This made the remainder of the mission, a flyby of the near-Earth asteroid Geographos, impossible. The spacecraft remained in geocentric orbit and continued testing the spacecraft components until the end of the mission.

[a] Regeon et al, "The Clementine Lunar Orbiter."

Table 4–73. Mars Observer Mission Characteristics

Launch Date/Launch Site	September 25, 1992/Cape Canaveral Air Force Station
Date of Reentry	Lost contact with spacecraft on August 22, 1993.
Launch Vehicle	Titan III with Transfer Orbit Stage
NASA Role	Project management, Mars Observer Laser Altimeter, Magnetometer/Electron Reflectometer, Pressure Modulator Infrared Radiometer
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	• Determine the global elemental and mineralogical character of Mars' surface material. • Define the planet's global topography and gravitational field. • Establish the nature of the Martian magnetic field. • Determine the time and space distribution, abundance, sources, and sinks of volatile material and dust over a seasonal cycle. • Explore the structure and aspects of the circulation of the Martian atmosphere.
Orbit Characteristics	Did not go into orbit around Mars
Weight	Total weight: 2,573 kg (5,672 lb) Payload weight: 156 kg (344 lb)
Dimensions	Launch configuration: 1.6 m by 2.2 m by 1.1 m (5.2 ft by 7.2 ft by 3.6 ft)[a] Spacecraft bus: 2.9 m by 2.9 m by 3.2 m (9.5 ft by 9.5 ft by 10.5 ft)[b] Solar panels (6): each 183 cm by 219 cm[c] (72 in by 86 in) Solar array area: 24.5 sq m[d] (263.7 sq ft)
Power Source	Solar arrays (six panels), two nickel cadmium batteries
Prime Contractor	Astro-Space Division of General Electric
Instruments and Experiments	• Mars Observer Camera (MOC) PI: Michael C. Malin, Malin Space Science Systems, Inc. The MOC was a line-scan camera designed to take low-resolution images of Mars on a daily basis for studies of the climate. The MOC also took medium-resolution and high-resolution images of selected areas to study surface geology and interactions between the surface and the atmosphere. • Thermal Emission Spectrometer (TES) PI: Philip R. Christensen, Arizona State University The TES was designed to map the mineral content of surface rocks, frosts, and the composition of clouds. • Mars Observer Laser Altimeter (MOLA) PI: David E. Smith, NASA Goddard Space Flight Center The MOLA was designed to measure the topographic relief of the Martian surface.

Table 4–73. Mars Observer Mission Characteristics (Continued)

Instruments and Experiments[e]	• Magnetometer/Electron Reflectometer (MAG/ER) PI: Mario H. Acuña, Goddard Space Flight Center The MAG/ER was designed to determine the nature of the magnetic field of Mars and its interactions with the solar wind. • Pressure Modulator Infrared Radiometer (PMIRR) PI: Daniel J. McCleese, Jet Propulsion Laboratory The PMIRR was designed to measure dust and condensates in the atmosphere, as well as profiles of temperature, water vapor, and dust opacity as they change with latitude, longitude, and season. • GRS Team Leader: William V. Boynton, University of Arizona The GRS was designed to measure the abundance of elements (uranium, thorium, potassium, iron, and silicon, for example) on the surface of Mars. • Radio Science Experiment: Team Leader: G. Leonard Tyler, Stanford University This experiment was designed to use the spacecraft radio with an ultrastable oscillator to measure atmospheric refractivity as it varied with altitude to determine the temperature profile of the atmosphere. The experiment also was designed to use tracking data to measure the gravity field of Mars.
Results	Unsuccessful. Contact was lost on August 22, 1993, while the spacecraft was preparing for its August 24 orbit insertion around Mars.
Remarks	It was believed that the spacecraft developed a critical leak in its propulsion system, sending it out of control. The spacecraft most likely flew past Mars and went into orbit around the Sun with an orbital period of approximately 500 days.[f]

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[a] "Mars Observer Press Kit," September 1992, p. 19 (NASA History Office Folder 16615).

[b] "Mars Observer," QuickLook, *http://msl.jpl.nasa.gov/QuickLooks/marsobsQL.html* (accessed August 11, 2005).

[c] "Mars Observer Press Kit."

[d] "Mars Observer," QuickLook.

[e] "Mars Observer," QuickLook. Also "Mars Observer Press Kit," pp. 34–35.

[f] "General Questions," Mars Global Surveyor, *http://mars.jpl.nasa.gov/mgs/faqs/faq_general.html* (accessed August 11, 2005).

Table 4–74. Mars Global Survey Mission Characteristics

Launch Date/Launch Site	November 7, 1996/Kennedy Space Center
Date of Reentry	No reentry. Completed primary mission on January 31, 2001. Still orbiting Mars as of mid-2005.
Launch Vehicle	Delta 7925
NASA Role	Project management, mission operations, science operations, PIs for the Mars Orbiter Laser Altimeter and Magnetometer/Electron Reflectometer investigations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	• To enhance the understanding of the geosciences and climatology of Mars. This will be accomplished by characterizing surface morphology at high spatial resolution to quantify surface characteristics and geologic processes; determining the composition and mapping the distribution of surface minerals, rocks, and ices; measuring the thermophysical properties of the surface; determining globally the topography, geodetic figure, and gravitational field; establishing the nature of the magnetic field and mapping the crustal remnant field; monitoring global weather and the thermal structure of the atmosphere; and studying surface-atmosphere interaction by monitoring surface features, polar caps, polar thermal balance, atmospheric dust, and condensate clouds over a seasonal cycle. • To provide multiple years of in-orbit relay communications capability for Mars landers and atmospheric probes for any nation interested in participating in international Mars exploration. • To support planning for future Mars missions through data acquisition, with special emphasis on those measurements that could impact landing site selection.[a] Program objectives: • Launch a spacecraft to Mars during the 1996 opportunity. • Insert the spacecraft into a near Sun synchronous polar orbit at Mars. • Carry out a global survey of Mars during one Martian year to collect at least 70 percent of the science data available for acquisition from the scientific instruments.
Orbit Characteristics Around Mars[b]	
Apogee	378 km (235 mi) average
Perigee	378 km (235 mi) average
Period (min)	120
Weight	2,337 lb (1,060 kg) fueled

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Dimensions	Bus: 5 ft by 5 ft by 10 ft (1.5 m by 1.5 m by 3 m); 40 ft (12 m) across with fully deployed solar panels; high gain antenna: 10 ft (3 m) deployed on a 6.5-ft (2-m) boom
Shape	Rectangular
Power Source	Solar arrays and batteries
Prime Contractor	Lockheed Martin
Instruments and Experiments	• TES: PI: Philip Christensen, Arizona State University The TES analyzed infrared radiation from the surface. From these measurements, scientists determined several important properties of the rocks and soils comprising the Martian surface, including the following: — The thermophysical properties of Martian surface materials. — The composition and surface distribution of Martian rock and soil and the past presence of water on Mars. — The growth and contraction of the polar ice caps, as well as the amount of radiation absorbed, reflected, and emitted by the caps and the composition of the ice. — The circulation and dynamics of the atmosphere during a Martian year, the atmospheric pressure and temperature distribution, and the long-term climate. — The composition and distribution of atmospheric dust and clouds. This information will extend and improve measurements of thermal infrared emission instruments carried by earlier missions (Mariners 6, 7, and 9 and Vikings 1 and 2).[c] • MOLA PI: David Smith, Goddard Space Flight Center The MOLA measured the height of Martian surface features. A laser fired pulses of infrared light 10 times each second, striking a 160-m (525-ft) area on the surface. By measuring the length of time it took for the light to return to the spacecraft, scientists determined the distance to the planet's surface. Data from this instrument gave scientists elevation maps precise to within about 30 m (100 ft). Scientists used these maps to construct a detailed topographic map of the Martian landscape.

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments	• MAG/ER PI: Mario Acuña, Goddard Space Flight Center The MAG/ER was used to search for evidence of a planetary magnetic field and measure its strength (if it existed). These measurements provided critical tests for current speculations about the early history and evolution of the planet. The instrument also scanned the surface to detect remnants of an ancient magnetic field, providing clues to the Martian past when the magnetic field may have been stronger due to the planet's higher internal temperature. Unlike the other instruments, the magnetometer sensors were not attached to the main body of the spacecraft. Instead, each one of the two sensors sat at opposite ends of the spacecraft at the tips of the spacecraft's two solar panels. This placement ensured that the data generated from the magnetometer sensors was not "polluted" by magnetic signals from the spacecraft system. The electron reflectometer sensor was mounted on the instrument platform because it was not sensitive to weak magnetic fields. The MAG and ER operated during the cruise phase of the mission. During the aerobraking phase, the spacecraft crossed the Martian bow shock formed by the supersonic interaction of the planet with the solar wind at least twice per orbit. The MAG/ER detected these crossings and generated valuable data for determining the global extent of the Martian magnetic field. During the mapping orbit, the MAG/ER operated continuously.[d] • Radio Science Team Leader: G. Leonard Tyler, Stanford University This instrument used data provided by the spacecraft's telecommunications system, high-gain antenna, and onboard ultra-stable oscillator to map variations in the gravity field by noting where the spacecraft speeded up and slowed down during its passage around Mars. From these observations, a precise map of the gravity field could be constructed and related to the structure of the planet. In addition, scientists studied how radio waves were distorted as they passed through the atmosphere of Mars to measure the atmosphere's temperature and pressure.

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments	• MOC PI: Michael Malin, Malin Space Science Systems Inc. The MOC was designed to obtain images of the surface and atmosphere of Mars to study the meteorology/climatology and geology of Mars. The camera's primary objectives were the following: — Obtain global, synoptic views of the Martian surface and atmosphere on a daily basis to understand the meteorological and climatological changes during the mission. — Monitor surface and atmospheric features for changes on temporal scales from hours to years and on a spatial scale necessary for resolving the details of their morphology. — Systematically examine local areas at high spatial resolution to quantify surface/atmosphere interactions and geologic processes operating on short timescales. • The MOC was the flight spare of the camera used on the Mars Observer mission and was essentially identical.[e] The MOC used a "push-broom" technique that built a long, ribbon-like image while the spacecraft passed over the planet. The camera provided low-resolution global coverage of the planet everyday, collecting images through red and blue filters. It also obtained medium-resolution and high-resolution images of selected areas. To acquire images to satisfy its objectives, the Mars Global Surveyor MOC consisted of a narrow-angle assembly and a wide-angle assembly. The wide-angle lens was used to accumulate a weather map of Mars each day showing surface features and clouds at a resolution of about 7.5 km (4.6 mi). These global views were similar to the types of views obtained by weather satellites orbiting Earth. The narrow-angle lens imaged small areas of the surface at a resolution of 2 m to 3 m (6.5 ft to 9.5 ft). These pictures were sharp enough to show small geologic features such as boulders and sand dunes; they may also be used to select landing sites for future missions.

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments	• Mars Relay Radio System (Relay Communications Experiment) PI: Jacques E. Blamont, CNES The Mars Global Surveyor carried a radio receiver/transmitter supplied by the French space agency CNES, which was originally designed to support the Russian Mars '94 mission (renamed Mars '96) but lost during launch. At the time of this mission, the system was planned to relay data from the microprobes carried on the upcoming 1998 Mars Global Surveyor Lander mission as well as serve as a backup for data relay from the lander itself. Data relayed from the surface to the Mars Global Surveyor was to be stored in the large solid-state memory of the orbiter's camera, where it would be processed for return to Earth. This collaborative effort would maximize data collection. Following support of the Mars '98 mission, the Mars relay system was expected to provide multiple years of in-orbit communications relay capability for future international Mars missions. The Mars Relay consisted of an 86-cm (33.8-in) high, 2.5-kg (5.5-lb) quadrifilar helix fiberglass antenna mast mounted on the spacecraft and an electronics box and coaxial cable. The system received data from the surface missions and routed them for storage to the large on-board storage memory buffer of the MOC. The stored transmissions were then routed to Earth via the MOC. The transmission frequency to the Mars ground stations was 437.1 MHz at 1.3 W. The receive frequencies (from the stations) were 401.5 MHz and 405.6 MHz. The antenna FOV ranged from limb to limb.[f]

Table 4–74. Mars Global Survey Mission Characteristics (Continued)

Instruments and Experiments[g]	- Accelerometer PI: Dr. Gerald M. Keating, Langley Research Center The accelerometer instrument measured changes in velocity as the spacecraft performed aerobraking maneuvers in the Martian thermosphere. The accelerometer data could be used to deduce atmospheric drag on the spacecraft so atmospheric densities could be estimated. The z-axis accelerometer was aligned closely to the spacecraft velocity vector. It had a sensitivity of 0.332 mm/sec per count, allowing measurements up to at least 170 km (106 mi) altitude. A typical set of accelerometer measurements during aerobraking spanned from about 200 seconds before periapsis to 200 seconds after periapsis, about 30 degrees of latitude. Additional measurements obtained before and after this period were used to determine accelerometer bias for each pass. Measurements were obtained every 0.1 second. Accelerations of 1 micro-g were detected.[h]
Results	At the end of 1998, the Mars Global Surveyor continued with excellent aerobraking performance. The orbital period was less than 3 hours. The spacecraft was very healthy. See the narrative above for science results.

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[a] "Mars Global Surveyor," Fact Sheet, Jet Propulsion Laboratory, *http://www.jpl.nasa.gov/news/fact_sheets/mgs.pdf* (accessed August 10, 2005).

[b] "Mars Global Surveyor," *http://nssdc.nasa.gov/planetary/marsurv.html* (accessed August 11, 2005).

[c] "Thermal Emission Spectrometer (TES)," NSSDC Master Catalog: Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=2* (accessed May 22, 2006).

[d] "The MGS Magnetometer and Electron Reflectometer," *http://mgs-mager.gsfc.nasa.gov/instrument.html* (accessed May 22, 2006).

[e] "Mars Orbiter Camera," NSSDC Master Catalog: Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=1* (accessed May 22, 2006).

[f] "Mars Relay Communications Experiment," NSSDC Master Catalog, Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=6* (accessed May 22, 2006).

[g] "Mars Global Surveyor Arrival Press Kit," September 1997, pp. 32–33, *http://www.jpl.nasa.gov/news/press_kits/mgsarriv.pdf* (accessed August 11, 2005).

[h] "Accelerometer," NSSDC Master Catalog: Experiments, *http://nssdc.gsfc.nasa.gov/database/MasterCatalog?sc=1996-062A&ex=7* (accessed May 22, 2006).

Table 4–75. Mars Pathfinder Mission Characteristics

Launch Date/Launch Site	December 4, 1996/Cape Canaveral Air Station
Date of Reentry	No reentry. Final data transmission: September 27, 1997.
Launch Vehicle	Delta II 7925/PAM-D
NASA Role	Project management; design, build, and operate Pathfinder
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives[a]	• Demonstrate a simple, less costly system at fixed price for placing a science payload on the surface of Mars at one-fifteenth the Viking price tag. • Demonstrate NASA's commitment to low-cost planetary exploration by completing the mission for a total cost of $280 million including the launch vehicle and mission operations. • Demonstrate the mobility and usefulness of a microrover on the surface of Mars. Rover mission objectives: Conduct technology experiments, science experiments, and mission experiments, specifically:[b] Technology Experiments — Mars Terrain Geometry Reconstruction from Imagery — Mars Basic Soil Mechanics — Mars Dead Reckoning Sensor Performance and Path Reconstruction/Recovery — Sinkage in Each Martian Soil Type — Logging/Trending of Vehicle Performance Data — Rover Thermal Characterization — Rover Imaging Sensor Performance — UHF Link Effectiveness — Material Abrasion — Material Adherence Rover Science Experiments — Alpha Proton X-Ray Spectrometer — APXS Deployment Mechanism — Imaging Mission Experiments — Lander Imaging — Damage Assessment
Weight	Lander: 1,1,973 lb (895 kg) fueled; 1,766 lb (801 kg) dry Rover: 23 lb (10.6 kg)
Dimensions	Lander: 3 ft (0.9 m) tall Rover: 2 ft (65 cm) long, 1.5 ft (48 cm) wide, 1 ft (30 cm) tall
Shape	Lander: tetrahedron, three sides, and base
Power Source	Solar panels, batteries
Prime Contractor	Jet Propulsion Laboratory

Table 4–75. Mars Pathfinder Mission Characteristics (Continued)

Instruments and Experiments	Lander: • Imager for Mars Pathfinder PI: Peter Smith, University of Arizona The Imager for Mars Pathfinder was a stereo imaging system with color capability provided by 11 individual geologic filters, four pairs of atmospheric filters, and two pairs of stereo filters. It had three physical subassemblies: 1) a camera head with the stereo imaging system; filter wheel; CCD; pre-amp; and mechanisms and stepper motors; 2) an extendable mast with electronic cabling; and 3) two plug-in electronics cards (CCD data card and power supply/motor drive card) that plugged into slots in the Warm Electronics Box within the lander. With its mast fully extended, the Imager for Mars Pathfinder stood 5 ft (1.5 m) above the ground. The close-up lens enabled the Pathfinder to take high-resolution shots of magnetic windblown dust that adhered to a special dust collector mounted on the Imager for Mars Pathfinder. Atmospheric investigations were carried out using Imager for Mars Pathfinder images including measuring aerosol opacity periodically by imaging the Sun through two narrowband filters; investigating magnetic properties; and observing wind direction using a small wind sock mounted above a reference grid and a calibration and reference target mounted to the lander. • ASI/MET package Instrument Definition Team Leader: Alvin Seiff, San Jose State University Science Team Leader: John T. "Tim" Schofield, NASA Jet Propulsion Laboratory The ASI/MET was an engineering subsystem that acquired atmospheric information during lander descent through the atmosphere and during the entire landed mission. The ASI/MET measured accelerations over a wide variety of ranges from the micro-g accelerations experienced upon entering the atmosphere to the peak deceleration and landing events in the range of 30g's to 50g's. Data acquired during the lander's entry and descent permitted reconstruction of profiles of atmospheric density, temperature, and pressure from altitudes above 100 km (60 mi) from the surface. It took advantage of the heritage provided by the Viking mission experiments.

Table 4–75. Mars Pathfinder Mission Characteristics (Continued)

Instruments and Experiments[c]	The ASI/MET depended on the attitude and information management subsystem of the lander. It consisted of sensors at three different heights and used windsocks to detect wind direction and speed. A wind sensor on top of the mast sensed temperature differences among six temperature sensors that measured wind speed and direction. A sensor on the base of the lander measured atmospheric pressure. • Magnets for measuring magnetic properties of soil. • Wind socks: Three wind socks were located at various heights on the meteorology mast to determine the speed and direction of winds at the Pathfinder landing site. The wind socks were imaged repeatedly by the Imager for Mars Pathfinder. The orientations of the wind socks were measured in the images to determine the wind velocity at three heights above the surface. This information was used to estimate the aerodynamic roughness of the surface in the vicinity of the lander and to determine the variation in wind speed with height. Because the earlier Viking landers had wind sensors at only one height, such a vertical wind profile was never measured on Mars. This new knowledge helped develop and modify theories of how dust and sand particles were lifted into the Martian atmosphere by winds, for example. Because erosion and deposition of wind-blown materials were such an important geologic process on the surface of Mars, the results of the wind sock experiment were of interest to geologists and atmospheric scientists. Rover: • Alpha Proton X-ray Spectrometer (APXS) PI: Rudolph Rieder, Max Planck Institute for Chemistry, Germany Co-investigators: Thanasis Economou, University of Chicago and Henry Wanke, Max Planck Institute for Chemistry, Germany This instrument determined the elements making up the rocks and soil on Mars. The APXS was derived from instruments flown on the Russian Vega and Phobos missions, and it was identical to the unit to fly on the Russian Mars '96 landers. The Mars Pathfinder rover mobility allowed the APXS to take spectral measurements of the Martian dust and move to distinct rock outcroppings, permitting analysis of native rock composition for the first time. • Three cameras. • Technology experiments.

Table 4–75. Mars Pathfinder Mission Characteristics (Continued)

Results	Extremely successful. The primary mission concluded on August 4, 1997. The final transmission was on September 25, 1997. The mission returned 2.3 billion bits of information, including more than 16,500 images from the lander, 550 images from the rover, and more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors.

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[a] "Mars Pathfinder Mission Objectives," *http://mpfwww.jpl.nasa.gov/MPF/mpf/mission_obj.html* (accessed August 23, 2005).

[b] "Rover Sojourner," *http://mpfwww.jpl.nasa.gov/MPF/rover/mission.html* (accessed August 23, 2005).

[c] "Mars Pathfinder Instrument Descriptions," *http://mpfwww.jpl.nasa.gov/MPF/mpf/sci_desc.html#IMP* (accessed August 23, 2005). Also "Mars Pathfinder Landing," Press Kit, July 1997, pp. 36–38, *http://www2.jpl.nasa.gov/files/misc/mpflanhq.pdf* (accessed May 2, 2006).

Table 4–76. Mars '96 Instruments

Instruments	Description
Orbiter instruments:	
Surface and Atmosphere Studies:	
Stereo-Spectral Imaging System	This system was designed to study the Martian surface and atmosphere and provide cartographic support for other experiments and future missions. It consisted of a Multifunctional High Resolution Stereoscopic TV Camera, a WAOSS Wide-Angle Stereoscopic TV Camera, and an OMEGA Visible and Infrared Mapping Spectrometer.
Planetary Fourier Spectrometer	This spectrometer would monitor three-dimensional temperature and pressure fields; perform global mapping of winds; study variations of water and carbon monoxide in space and time; and investigate the optical depth, phase function, size distribution, and chemical composition of aerosols.
Mapping Radiometer	This radiometer was designed to investigate the thermal inertia of the Martian soil and the diurnal and seasonal dynamics of the temperature regime. It also was designed to search for anomalous heat sources and conduct thermal studies of the atmosphere.
High Resolution Mapping Spectrophotometer	This spectrophotometer would perform spectrophotometry of the planet in absorption bands of some rocks that may exist on the Martian surface to determine the surface composition. It also would study the nature of aerosols by measuring spectral and angular distributions of brightness both above the planetary limb and of certain cloud-covered areas.
Multichannel Optical Spectrometer	This spectrometer was designed to observe vertical concentration profiles of ozone, water vapor, carbon monoxide, oxygen, dust, and temperature in the middle and lower atmosphere. It also was designed to measure the global distribution of water vapor.
Ultraviolet Spectrophotometer	This spectrophotometer would measure hydrogen, helium, and oxygen distributions in the upper atmosphere of Mars; determine deuterium abundance in the Martian atmosphere; observe high-altitude temperature profiles of the atmosphere; and observe the neutral component of the interstellar-interplanetary medium.
Long-Wave Radar	This radar would study the underlying surface structure of the Martian cryolithospheres, determine the depth of occurrence of ice-bearing rocks and their geographic distribution, and estimate the dielectric parameters of soil. The radar would measure the global distribution of height profiles of electron number-density in the Martian upper ionosphere to study the dynamics of the solar wind interaction with the Martian upper atmosphere.

Table 4–76. Mars '96 Instruments (Continued)

Instruments	Description
Gamma-ray Spectrometer	This spectrometer was designed to perform geochemical mapping of the elemental composition of Martian surface rocks; the spectrometer used high spatial resolution and accuracy to determine the abundance of natural radioactive elements, basic rock-forming elements, and minor elements.
Neutron Spectrometer	This spectrometer was designed to determine the water content in the surface layer of Martian soils.
Quadrupole Mass Spectrometer	This spectrometer would determine the composition of the Martian upper atmosphere and ionosphere; measure height profiles of the atmospheric ion and neutral composition; and measure seasonal and diurnal variations of the Martian upper atmosphere and ionosphere.
Plasma Physics:	
Energy-Mass Ion Spectrograph and Neutral-Particle Imager	This instrument was designed to study the interaction between the plasma and neutrals near Mars and investigate plasma ion composition. The instrument consisted of an ion-mass imaging spectrometer, two neutral particle imagers, and a scanner platform.
Fast Omnidirectional Non-Scanning Energy-Mass Analyzer	This analyzer would investigate the structure, dynamics, and origin of plasma formations in the near-Mars space. The analyzer used measurements of three-dimensional distribution of hot ions and flux parameters with high time resolution.
Omnidirectional Ionospheric Energy-Mass-Spectrometer	This spectrometer was designed to study the dynamics of the Martian ionosphere and the ion composition of the thermal plasma of ionospheric origin in the magnetosphere of Mars.
Ionospheric Plasma Spectrometers	These two spectrometers would measure the Martian ionosphere and the cold plasma convection in the Martian magnetosphere. The instrument consisted of two identical ion energy spectrometers; a set of 28 retarding potential analyzers, a spherical ion probe; and a spherical retarding potential analyzer operating in a floating mode with periodic measurements of integral cold ion energy spectra.
Electron Analyzer and Magnetometer	This instrument would measure, with high accuracy and high time resolution, the three-dimensional distribution of electron velocity and magnetic field vector in the plasma environment of Mars and the solar wind.
Wave Complex	This instrument was designed to study the Martian magnetosphere oblateness by the solar wind and of the energy transfer through the shock and planetopause; identify instabilities in the ionosphere and magnetosphere; and study waves of atmospheric origin generated by sand storms and lightning.
Low-Energy Charged Particle Spectrometer	This spectrometer would carry out detailed studies of energetic particle radiation in the Martian environment and monitor low-energy cosmic rays along the Earth-to-Mars trajectory.

Table 4–76. Mars '96 Instruments (Continued)

Instruments	Description
Astrophysics and Cruise:	
Precision Gamma Spectrometer	This spectrometer was designed to measure gamma radiation from the Martian surface, powerful solar flares, and gamma-ray bursts. The spectrometer would operate continuously along the Earth-to-Mars trajectory while recording cosmic gamma rays. In orbit around Mars, the instrument would measure gamma spectra of the surface.
Cosmic and Solar Gamma-Burst Spectrometer	This spectrometer would carry out high-precision localization of gamma-ray burst sources using data from Ulysses and near-Earth satellites.
Stellar Oscillation Photometer	This photometer would study pulsations, rotations, and the internal structure of stars through long-term, continuous, and high-accuracy photometry of stars along the Earth-to-Mars trajectory.
Solar Oscillation Photometer	This photometer would study the Sun's internal structure from measurements of solar brightness oscillations through long-term, continuous, and high-accuracy photometry of the Sun along the Earth-to-Mars trajectory.
Radiation/Dosimetry Control Complex	This instrument was intended to study radiation conditions along flight trajectories to Mars and near the planet and determine the energy spectra; measure the Sun's x-ray flux; identify the mass composition of charged particle fluxes; and determine the spatial distribution of charged particle fluxes within a wide energy range.
Small Station scientific payload:	
Meteorology Instrument System	This system consisted of temperature sensors; an absolute pressure sensor; a relative humidity sensor; an optical depth sensor; and an ion anemometer.
Descent Phase Instrument System	This system included an accelerometer, as well as pressure and temperature sensors.
Alpha-particle, Proton and X-ray Spectrometer	This spectrometer performed measurements of the elemental composition of Martian soils beginning with carbon.
Seismometer, Magnetometer, and Inclinometer	This instrument consisted of a three-component magnetometer with an inclinometer on the boom, a vertical-component seismometer, and an electronics unit.
Panoramic Camera	This camera took a TV panorama of the Martian landscape around the small station.
Descent Camera	This camera performed imaging with a resolution of 20 m (65.6 ft) to 1 cm (0.4 in) during parachute descent.
Mars Oxidant Experiment	This experiment studied the presence of an oxidizing agent in the Martian soil and atmosphere inferred from the results of biology experiments on board the Viking landers in the mid-1970s.

Table 4–77. Mars Climate Orbiter Mission Characteristics

Launch Date/Launch Site	December 11, 1998/Cape Canaveral Air Force Station
Date of Reentry	None; lost contact
Launch Vehicle	Delta II 7425
NASA Role	Mission design; spacecraft and payload development, integration, testing, and launch; mission operations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	(Same mission objectives for Climate Orbiter and Polar Lander missions)[a] • Develop and launch two spacecraft to Mars during the 1998 Mars transfer opportunity. • One orbiter and one lander spacecraft. • Separate Med-Lite launch vehicles. • Development cost capped at $183.9 million (real-year dollars). • Collect and return to Earth science data resulting from the in situ and remote investigations of the Martian environment by the Lander and Orbiter spacecraft. • Landing site targeted near south pole (~80°S). • 90-day primary lander mission. • 400-km (249-mi) near-circular, near-polar mapping orbit. • Two-year science mapping, five-year data relay mission. Climate Orbiter science objectives: • Analyze the composition of surface materials, characterize daily and seasonal weather patterns and frost deposits, and monitor surface and atmospheric interactions to better understand the planet as a global system. • Study variations in atmospheric dust and volatile materials, such as carbon dioxide and water, in both their vapor and frozen forms; track these variations during a full Martian year (687 Earth days). • Identify surface reservoirs of volatile material and dust and observe their seasonal variations. Use the orbiter's imager and sounder to characterize surface compositional boundaries and changes that might occur with time or seasons.

Table 4–77. Mars Climate Orbiter Mission Characteristics (Continued)

Mission Objectives	• Explore climate processes that stir up or quell regional and global dust storms, as well as atmospheric processes transporting volatiles such as water ice clouds and dust around the planet. • Search for evidence of Mars' ancient climate, which some scientists believe was temperate and more Earth-like with a thicker atmosphere and abundant flowing water. Layered terrain in the polar regions suggests more recent, possibly cyclic, climate change. Studies of Mars' early climate compared with Earth's may explain whether internal or external factors (such as changes in Mars' orbit) are primary drivers of climate change.
Orbit Characteristics	Did not enter orbit
Weight	629 kg (1,387 lb) total, consisting of 338 kg (745 lb) spacecraft and 291 kg (642 lb) fuel
Dimensions	Main bus: 2.1 m (6.9 ft) tall, 1.6 m (5.4 ft) wide, 2 m (6.4 ft) deep; solar array wingspan: 5.5 m (18 ft) tip to tip
Power Source	Solar array
Prime Contractor	Lockheed Martin
Instruments and Experiments	• Mars Color Imager (MARCI) PI: Michael Malin, Malin Space Science Systems Inc. The MARCI combined nadir-pointed pushframe wide-angle and medium-angle cameras. Near the end of the Orbiter's cruise phase, the MARCI acquired approach images of Mars. • Pressure Modulator Infrared Radiometer (PMIRR) PIs: Daniel McCleese, Jet Propulsion Laboratory and Vassili Moroz, Space Research Institute, Moscow The PMIRR was a nine-channel limb and nadir-scanning atmospheric sounder designed to vertically profile atmospheric temperature, dust, water vapor, and condensate clouds. The PMIRR also was designed to quantify surface radiative balance.
Results	Unsuccessful; was lost on arrival at Mars on September 23, 1999.

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[a] "Mars Climate Orbiter/Mars Polar Lander Mission Overview," *http://mars.jpl.nasa.gov/msp98/mission_overview.html* (accessed August 24, 2005).

Table 4–78. Mars Polar Lander Mission Characteristics

Launch Date/Launch Site	January 3, 1999/Cape Canaveral Air Station
Date of Reentry	None; lost at arrival at Mars
Launch Vehicle	Delta II 7425
NASA Role	Program management
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	(Same mission objectives for Climate Orbiter and Polar Lander missions)[a] Science objectives: • Land on the layered terrain in Mars' south polar region. • Search for evidence relating to ancient climates and more recent periodic climate change. • Present a picture of the current climate and seasonal change at high latitudes; in particular, present a picture of the exchange of water vapor between the atmosphere and ground. • Search for near-surface ground ice in the polar regions and analyze the soil for physically and chemically bound carbon dioxide and water. • Study surface morphology (forms and structures), geology, topography, and weather of the landing site.
Orbit Characteristics	None; did not enter orbit
Weight	Lander: 1,270 lb (576 kg) total, consisting of 639-lb (290-kg) lander and 141 lb (64 kg) of propellant, 181-lb (82-kg) cruise stage, 309-lb (140-kg) aeroshell and heat shield Deep Space 2: 7.9 lb (3.9 kg) total
Dimensions	Lander: 3.5 ft (1.06 m) tall, 12 ft (3.6 m) wide Deep Space 2: aeroshell 11 in (275 mm) high, 14 in (350 mm) diameter; enclosing a forebody (penetrator) 4.2 in (105.6 mm) long, 1.5 in (39 mm) diameter; and an aftbody (ground station) 4.1 in (105.3 mm) high (plus 5-in (127-mm) antenna), 5.3 in (136 mm) diameter
Power Source	Solar panels (lander), batteries (Deep Space 2)
Prime Contractor	Lockheed Martin
Instruments and Experiments	Lander: • Mars Volatiles and Climate Surveyor instrument suite: This instrument suite was designed to perform *in situ* investigations to address the science theme "Volatiles and Climate History" on Mars and to conduct meteorology, imaging, and soil composition experiments. This integrated package included a surface stereo imager; robotic arm with camera; meteorology package; and thermal and evolved gas analyzer. — Surface stereo imager PIs: Peter Smith, University of Arizona and H. Uwe Keller, Max Planck Institut für Aeronomie, Germany

Table 4–78. Mars Polar Lander Mission Characteristics (Continued)

Instruments and Experiments	— Meteorology package Co-investigators: David Crisp and Randy May, NASA Jet Propulsion Laboratory and Ari-Matti Harri, Finnish Meteorological Institute — Thermal and evolved gas analyzer PI: William Boynton, University of Arizona • Mars Descent Imager: PI: Michael Malin, Malin Space Science Systems Inc. The imager was to take approximately 30 pictures as the lander descended toward the surface of Mars, beginning just before heat-shield ejection at an altitude of about 5 mi (8 km) and continuing until landing. • LIDAR instrument: PI: V.S. Linkin, IKI, Russia The LIDAR instrument was supplied by the Russian Space Agency. This instrument emitted pulses of energy and then detected their echo while they bounced off material in the atmosphere. The instrument carried a microphone in its electronics box. Deep Space 2: • Sample collection/water detection experiment • Soil thermal experiment • Atmospheric descent accelerometer • Impact accelerometer
Results	Lost on arrival at Mars on December 3, 1999.

[a] "Mars Climate Orbiter/Mars Polar Lander Mission Overview," *http://mars.jpl.nasa.gov/msp98/mission_overview.html* (accessed August 24, 2005).

Table 4–79. Cassini-Huygens Mission Characteristics

Launch Date/Launch Site	October 15, 1997/Cape Canaveral Air Force Station
Date of Reentry	Operating as of mid-2005.
Launch Vehicle	Titan IVB/Centaur
NASA Role	Project management, spacecraft operations
Responsible (Lead) Center	Jet Propulsion Laboratory
Mission Objectives	Science objectives:[a] Saturn • Determine the temperature field, cloud properties, and composition of Saturn's atmosphere. • Measure the planet's global wind field, including waves and eddies; make long-term observations of cloud features to see how they grow, evolve, and dissipate. • Determine the internal structure and rotation of the deep atmosphere. • Study daily variations and relationships between the ionosphere and the planet's magnetic field. • Determine the composition, heat flux, and radiation environment present during Saturn's formation and evolution. • Investigate sources and nature of Saturn's lightning. Titan • Determine the relative amounts of different components of the atmosphere; determine the mostly likely scenarios for the formation and evolution of Titan and its atmosphere. • Observe vertical and horizontal distributions of trace gases; search for complex organic molecules; investigate energy sources for atmospheric chemistry; determine the effects of sunlight on chemicals in the stratosphere; study formation and composition of aerosols (particles suspended in the atmosphere). • Measure winds and global temperatures; investigate cloud physics, general circulation, and seasonal effects in Titan's atmosphere; search for lightning. • Determine the physical state, topography, and composition of Titan's surface; characterize its internal structure. • Investigate Titan's upper atmosphere, its ionization, and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Mission Objectives	Magnetosphere • Determine the configuration of Saturn's magnetic field, which is nearly symmetrical with Saturn's rotational axis. Also, study the field's relation to the modulation of Saturn kilometric radiation—a radio emission from Saturn believed to be linked to the way electrons in the solar wind interact with the magnetic field at Saturn's poles. • Determine the current systems, composition, sources, and concentrations of electrons and protons in the magnetosphere. • Characterize the structure of the magnetosphere and its interactions with the solar wind and with Saturn's moons and rings. • Study how Titan interacts with the solar wind the ionized gases within Saturn's magnetosphere. The Rings • Study the configuration of the rings and dynamic processes responsible for ring structure. • Map the composition and size distribution of ring material. • Investigate the interrelation of Saturn's rings and moons, including imbedded moons. • Determine the distribution of dust and meteoroid distribution in the vicinity of the rings. • Study the interactions between the rings and Saturn's magnetosphere, ionosphere, and atmosphere. Icy Moons • Determine the general characteristics and geological histories of Saturn's moons. • Define the different physical processes that have created the surfaces, crusts, and subsurfaces of the moons. • Investigate compositions and distributions of surface materials, particularly dark, organic-rich materials and condensed ices with low melting points. • Determine the bulk compositions and internal structures of the moons. • Investigate interactions of the moons with Saturn's magnetosphere and ring system; investigate possible gas injections into the magnetosphere.
Weight	Cassini: 5,712 kg (12,593 lb) with fuel and Huygens probe; Cassini orbiter alone (unfueled): 2,125 kg (4,685 lb) Huygens: 320 kg (705 lb)
Dimensions	Cassini: 6.8 m (22.3 ft) high, 4 m (13.1 ft) wide Boom: 11 m (36 ft) Huygens: 2.7 m (8.9 ft) diameter
Shape	Main body: cylindrical

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Power Source	Radioisotope thermoelectric generators
Prime Contractor	Lockheed Martin
Instruments and Experiments	Orbiter Instruments: • Cassini Plasma Spectrometer (CAPS) PI: David T. Young, Southwest Research Institute The CAPS is a direct sensing instrument measuring the energy and electrical charge of particles, such as electrons and protons, that the instrument encounters. The CAPS measures the molecules originating from Saturn's ionosphere and determines the configuration of Saturn's magnetic field. The CAPS also investigates plasma in these areas as well as the solar wind within Saturn's magnetosphere. • Cosmic Dust Analyzer (CDA) PI: Eberhard Grün, Max Planck Institute für Kernphysik, Germany The CDA is a direct sensing instrument measuring the size, speed, and direction of tiny dust grains near Saturn. Some of these particles orbit Saturn while others may come from different solar systems. Cassini's CDA is more advanced than corresponding instruments on the Galileo and Ulysses spacecraft. Cassini's CDA also can determine trajectories (orbits), speeds, and chemical compositions of the dust particles impacting the Saturn system, allowing scientists to determine where the dust originated. • Composite Infrared Spectrometer (CIRS) PI: Virgil G. Kunde, Goddard Space Flight Center The CIRS is a remote sensing instrument measuring the infrared light coming from an object (such as an atmosphere or moon surface) to learn about its temperature and composition. The CIRS measures infrared emissions from atmospheres, rings, and surfaces in the Saturn system to determine their composition, temperatures, and thermal properties. The spectrometer maps in three dimensions to determine temperature and pressure profiles with altitude, gas composition, and the distribution of aerosols and clouds.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	The CIRS evolved from the Voyager Infrared Interferometer Spectrometer (IRIS) and is a significant improvement, with a spectral resolution 10 times greater than IRIS. A larger wavelength range is covered, with more closely spaced data points, greatly increasing the details able to be seen in the spectrum. A narrow angle camera is also built into a reflecting telescope with a 2,000-mm (79-inch) focal length and 0.35-degree FOV. The CIRS consists of two combined interferometers, operating in the far-infrared (10 cm^{-1}–600 cm^{-1}) and mid-infrared (600 cm^{-1}–1,400 cm^{-1}). The two interferometers share a common telescope and scanner. The instrument also can observe the dark side of Saturn, view lightning, and make other readings normally obscured by the Sun. It can also look at Saturn's aurora for changes in temperature. • Ion and Neutral Mass Spectrometer (INMS) Team Leader: J. Hunter Waite, Southwest Research Institute The INMS is a direct sensing instrument analyzing charged particles (such as protons and heavier ions) and neutral particles (such as atoms) near Titan and Saturn to learn more about their atmospheres. It also measures the positive ion and neutral environments of Saturn's icy satellites and rings. • Imaging Science Subsystem (ISS) Team Leader: Carolyn C. Porco, University of Arizona The ISS is a remote sensing instrument that captures images in visible, infrared, and UV light. The ISS includes two cameras: a Wide Angle Camera (WAC) and a Narrow Angle Camera (NAC). The WAC takes a broad, wide-angle picture. The NAC has higher resolution and can record small areas in fine detail. The NAC can see a penny 1.5 cm (0.5 in) across from a distance of nearly 4 km (2.5 mi). The ISS returns thousands of images of Saturn and its rings and moons. Each camera uses a sensitive CCD as its detector. Each CCD consists of a 1,024 square array of pixels, 12 microns on a side. The camera's system allows for many data collection modes, including on-chip data compression. Both cameras are fitted with spectral filters that rotate on a wheel to view different bands within the electromagnetic spectrum ranging from 0.2 micron to 1.1 microns. At Saturn, the cameras observe the planet's atmosphere and cloud turbulence in different spectral wavelengths. In this way, the instrument can see both horizontal and vertical layers. They also study Saturn's rings and the surfaces of Saturn's moons.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	• Dual Technique MAG PI: David J. Southwood, Imperial College of Science & Technology, U.K. The MAG is a direct sensing instrument measuring the strength and direction of the magnetic field around Saturn. The magnetic fields are generated partly by the intensely hot molten core at Saturn's center. Measuring the magnetic field is one way to probe Saturn's extremely hot core. The MAG consists of a vector/scalar helium magnetometer sensor; a fluxgate magnetometer sensor; a data processing unit; three power supplies; and operating software and electronics associated with the sensors. • Magnetospheric Imaging (MIMI) Mass Spectrometer PI: Stamatios Krimigis, The Johns Hopkins University The MIMI Mass Spectrometer is a direct and remote sensing instrument that produces images and other data about particles trapped in Saturn's huge magnetosphere. This information is used to study the overall configuration and dynamics of the magnetosphere and its interactions with the solar wind, Saturn's atmosphere, Titan, rings, and icy satellites. The MIMI Mass Spectrometer studies all possible sources of energy in and around Saturn, the hot plasma in Saturn's magnetosphere, as well as storms and Saturn kilometric radiation. • Radio Detection and Ranging (RADAR) Instrument Team Leader: Charles Elachi, Jet Propulsion Laboratory The RADAR instrument is a remote active and remote passive sensing instrument producing maps of Titan's surface and measuring the height of surface objects by bouncing radio signals off the surface and timing their return. Radio waves can penetrate the thick veil of haze surrounding Titan. The RADAR instrument also listens for radio waves that Saturn or its moons may produce. The RADAR instrument operates in three ways: imaging, altimetry, and radiometry. Each mode allows the collection of different types of data, from straightforward imaging to three-dimensional modeling to passive collection of information, such as recording the energy emanating from a planet's surface. The RADAR instrument offers the opportunity to observe and map the synchrotron emissions at a new frequency (13.8 GHz) that is not possible from Earth-based telescopes. This opportunity comes from the Cassini radiometer's capability to separate the atmospheric thermal emission from synchrotron emission.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	• Radio and Plasma Wave Science (RPWS) Instrument PI: Donald A. Gurnett, University of Iowa The RPWS instrument is a direct and remote sensing instrument that receives and measures radio signals coming from Saturn, including radio waves given off by the interaction of the solar wind with Saturn and Titan. The RPWS instrument measures the electric and magnetic wave fields in the interplanetary medium and planetary magnetospheres. The instrument also determines the electron density and temperature near Titan and in some regions of Saturn's magnetosphere. The RPWS instrument studies the configuration of Saturn's magnetic field and its relationship to Saturn kilometric radiation, as well as monitoring and mapping Saturn's ionosphere, plasma, and lightning from Saturn's atmosphere. The RPWS instrument also determines dust and meteoroid distributions throughout the Saturn system and between the icy satellites, the rings, and Titan. • Radio Science Subsystem (RSS) Team Leader: Arvydas Kliore, Jet Propulsion Laboratory The RSS detects small changes in the phase and/or amplitude of a radio signal starting at the spacecraft and traveling to antennae on Earth. These small changes provide detailed information on several subjects including planetary gravitational fields, the mass of a moon, the structure of planetary rings, and the atmospheric and ionospheric structure of planets and moons. The RSS is unique in that only half of the instruments are carried aboard Cassini. The other half of instruments stays on Earth in the DSN complexes. While touring Saturn, the RSS instrument performs a series of radio occultations of Saturn's rings and atmosphere. An occultation is performed when Cassini sends a radio signal from the spacecraft through the rings to Earth. The information received on Earth gives scientists clues into the structure of the ring system. Similar occultations are performed on Saturn's atmosphere, allowing scientists to gather information on the global temperature, pressure, and zonal winds in Saturn's upper atmosphere. The RSS uses the spacecraft X-band communication link, S-band downlink, and Ka-band uplink and downlink for data acquisition.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	• Ultraviolet Imaging Spectrograph (UVIS) PI: Larry L. Esposito, University of Colorado, Boulder The UVIS is a remote sensing instrument that captures images of UV light reflected off objects, such as the clouds of Saturn and its rings, to learn more about their structure and composition. Designed to measure UV light over wavelengths from 55.8 nm to 190 nm, this instrument also helps determine the composition, distribution, aerosol particle content, and temperatures of their atmospheres. This instrument differs from other types of spectrometers in that it can take both spectral and spatial readings. It is particularly adept at determining the composition of gases. Spatial observations take a wide-by-narrow view, only one pixel tall and 60 pixels across. The spectral dimension is 1,024 pixels per spatial pixel. Additionally, it can take so many images that it can create movies to show how material is moved by other forces. • Visual and Infrared Mapping Spectrometer (VIMS) PI: Robert H. Brown, University of Arizona The VIMS is a remote sensing instrument consisting of two cameras in one: the first measures visible wavelengths, and the second detects infrared to learn more about the composition of moon surfaces, the rings, and the atmospheres of Saturn and Titan. The VIMS also observes the sunlight and starlight passing through the rings to learn more about ring structure. The VIMS measures reflected and emitted radiation from atmospheres, rings, and surfaces over wavelengths from 0.35 micrometer to 5.1 micrometers. It also helps determine the compositions, temperatures, and structures of these objects. Scientists use the VIMS to perform long-term studies of cloud movement and morphology in the Saturn system to determine the planet's weather patterns. The VIMS measures the locations where, and under what conditions, "pre-biotic" materials (the minor building blocks of life) are found to possibly provide clues about the origins of life. The VIMS also studies lightning and the planet's moons.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments	Probe Instruments: • Huygens Atmospheric Structure Instrument: PI: Marcello Fulchignoni, Paris Observatory, France This instrument contains a suite of sensors measuring the physical and electrical properties of Titan's atmosphere. Accelerometers measure forces in all three axes as the probe descends through the atmosphere. Since the aerodynamic properties of the probe are already known, it is possible to determine the density of Titan's atmosphere and detect wind gusts. If the probe lands on a liquid surface, this instrument would be able to measure the probe motion due to waves. • Temperature and pressure sensors also measure the thermal properties of the atmosphere. The Permittivity and Electromagnetic Wave Analyzer component measures the electron and ion conductivities of the atmosphere and searches for electromagnetic wave activity. On the surface of Titan, the analyzer measures the conductivity and permittivity (i.e., the ratio of electric flux density produced to the strength of the electric field producing the flux) of the surface material. • Doppler Wind Experiment (DWE) PI: Michael K. Bird, University of Bonn, Germany The DWE measures the wind speed during Huygens's descent through Titan's atmosphere by observing changes in the carrier frequency of the probe due to the Doppler effect. • Descent Imager/Spectral Radiometer (DISR) PI: Martin G. Tomasko, University of Arizona The DISR makes a range of imaging and spectral observations using several sensors and fields of view. By measuring the upward and downward flow of radiation, the radiation balance or imbalance of the thick Titan atmosphere is measured. Solar sensors measure the light intensity around the Sun due to scattering by aerosols in the atmosphere. This permits calculation of the size and number density of the suspended particles. Two imagers (one visible, one infrared) observe the surface during the latter stages of the descent and, as the probe slowly rotates, build a mosaic of pictures around the landing site. A side-view visible imager also obtains a horizontal view of the horizon and the underside of the cloud deck. For spectral measurements of the surface, a lamp switches on shortly before landing, augmenting the weak sunlight.

Table 4–79. Cassini-Huygens Mission Characteristics (Continued)

Instruments and Experiments[b]	• Gas Chromatograph Mass Spectrometer (GCMS) PI: Hasso B. Neimann, Goddard Space Flight Center A versatile gas chemical analyzer identifying and measuring chemicals in Titan's atmosphere, the GCMS is equipped with samplers filled at high altitude for analysis. The spectrometer builds a model of the molecular masses of each gas, and the gas chromatograph accomplishes a more powerful separation of molecular and isotopic species. During descent, the GCMS analyzes pyrolysis products (samples altered by heating) passed to it from the Aerosol Collector Pyrolyser. Finally, the GCMS measures the composition of Titan's surface after a safe landing. This investigation is made possible by heating the GCMS instrument just before impact to vaporize the surface material on contact. • Aerosol Collector and Pyrolyser (ACP) PI: Guy M. Israel, Service d'Aeronomie du Centre National de la Recherche Scientifique, France The ACP draws in aerosol particles from the atmosphere through filters, then heats the trapped samples in ovens to vaporize volatiles and decompose the complex organic materials. The products are then flushed along a pipe to the GCMS instrument for analysis. Two filters are provided to collect samples at different altitudes. • The Surface-Science Package (SSP) PI: John C. Zarnecki, University of Kent, UK The SSP contains sensors to determine the physical properties of Titan's surface at the point of impact. These sensors also determine whether the surface is solid or liquid. An acoustic sounder, activated during the last 100 meters (328 feet) of the descent, continuously determines the distance to the surface, measuring the rate of descent and the surface roughness (due to waves, for example). During descent, measurements of the speed of sound provide information on atmospheric composition and temperature, and an accelerometer accurately records the deceleration profile at impact, providing information on the hardness and structure of the surface. A tilt sensor measures any pendulum motion during the descent and indicates the probe attitude after landing.
Results	Successfully traveled to Saturn and inserted probe into Titan.

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[a] "Cassini Launch Press Kit," *http://www.jpl.nasa.gov/news/press_kits/cassini.pdf* (accessed August 16, 2005).

[b] "Spacecraft–Cassini Orbiter Instruments," *http://saturn.jpl.nasa.gov/spacecraft/instruments-cassini-intro.cfm* (accessed August 16, 2005). Also "Spacecraft–Huygens Probe Instruments," *http://saturn.jpl.nasa.gov/spacecraft/instruments-huygens.cfm* (accessed August 16, 2005).

Table 4–80. Voyager Events

Date	Event
1977	Mariner Jupiter/Saturn 1977 is renamed Voyager.
August 20, 1977	Voyager 2 launched from Kennedy Space Flight Center.
September 5, 1977	Voyager 1 launched from Kennedy Space Flight Center. Voyager 1 returns first spacecraft photo of Earth and Moon.
March 5, 1979	Voyager 1 makes its closest approach to Jupiter.
July 9, 1979	Voyager 2 makes its closest visit of Jupiter.
November 12, 1980	Voyager 1 flies by Saturn. Voyager 1 begins its trip out of the solar system .
August 25, 1981	Voyager 2 flies by Saturn.
1982	The DSN upgrades two 26-m antennae to 34-m.
January 24, 1986	Voyager 2 has the first-ever encounter with Uranus. NASA's DSN begins upgrades including expansion of 64-m antennae to 70-m.
1987	Voyager 2 "observes" Supernova 1987A.
1988	Voyager 2 returns first color images of Neptune.
August 25, 1989	Voyager 2 is the first spacecraft to observe Neptune. Voyager 2 begins its trip out of the solar system, below the ecliptic plane.
January 1, 1990	Begins Voyager Interstellar Mission.
February 14, 1990	Last Voyager Images–Portrait of the solar system.
February 17, 1998	Voyager 1 passes Pioneer 10 to become the most distant human-made object in space.

Table 4–81. Astro Mission Characteristics

Launch Date	Astro-1: December 2, 1990 Astro-2: March 2, 1995
Platform	Astro-1: STS-35 Astro-2: STS-67
Lead NASA Center	Marshall Space Flight Center
Instruments/Experiments	• HUT PI: Arthur F. Davidsen, The Johns Hopkins University The HUT recorded spectra in the 425-angstrom to 1,850-angstrom wavelength range, with emphasis on the largely unexplored region between 900 angstroms and 1,200 angstroms. It weighed 1,700 lb (771 kg); was 12 ft (3.7 m) long and 4 ft (1.2 m) wide; had a 0.9 meter (36-in) f/2.0 primary mirror and prime focus; and had a Rowland-circle design spectrograph. The primary mirror was coated with iridium for high reflectivity in the UV bandwidth. It had a collecting area of 5,300 sq cm (822 sq in), and at the focal plane the scale was 115 arc seconds per mm. The spectrograph separated UV light from an astronomical object into its component wavelengths for detailed analysis. The spectrograph consisted of an aperture wheel assembly, a 200-mm (7.9-in) osmium-coated concave grating, and a photon-counting detector. The detector included a microchannel plate intensifier with a cesium iodide photocathode array (pulse counting) with 1,024 channels. The spectrograph resolution was 75 microns. Using the first order of the grating permitted observations in the 850-angstrom to 1850-angstrom region, with a resolution of about 3 angstroms. In addition, the second order of the grating could also provide access to the 425-angstrom to 925-angstrom region with 1.5-angstrom resolution. The spectrograph recorded the UV spectrum electronically and transmitted the information to Earth for study. The spectrograph operated in four distinct modes: histogram mode, high-time resolution mode, cumulative unprocessed mode, and single scan mode. The first two modes were used in flight for observations of astrophysical objects. The last two modes were unprocessed modes used only for diagnostic purposes.

Table 4–81. Astro Mission Characteristics (Continued)

Instruments/Experiments	• UIT PI: Theodore P. Stecher, Goddard Space Flight Center The UIT obtained deep, wide-field UV images of the sky in the 1,200-angstrom to 3,200-angstrom range. It had the largest FOV of any sensitive UV imaging system planned for flight in the 1990s and was sensitive enough to record a blue star of 25th magnitude during a 30-minute exposure. The UIT was a 38-cm (15-in) f/9 Ritchey Chretien telescope with two selectable cameras mounted behind the primary mirror. The focal length of the primary mirror was 352.9 cm (139 in), and the nominal pixel size after digitization was 20 microns. Each camera had a six-position filter wheel to accommodate metal-dielectric interference filters, crystalline plates, or fused quartz. The first camera had a CsTe photocathode and was designed to operate in the 1,250-angstrom to 3,000-angstrom range. The second camera had a CsI photocathode and was designed to operate in the 1,200-angstrom to 1,700-angstrom range. The cameras were magnetically focused two-stage image intensifiers, which produced images recorded on 70-mm film. The resulting images covered a 40-arc-minute FOV, with a resolution of 3 arc seconds. Each unit contained 1,000 frames of astronomical film. Developed after the mission, each frame of film was digitized to form a 2,048 pixel by 2,048 pixel array for computer analysis.[a] • Wisconsin Ultraviolet Photopolarimeter Experiment (WUPPE) PI: Arthur D. Code, University of Wisconsin, Madison The WUPPE made the first high-quality, high signal-to-noise-ratio polarization measurements of faint UV sources in the 1,400-angstrom to 3,200-angstrom range with a FOV of 3.3 arc minutes by 4.4 arc minutes and a resolution of 6 angstroms. This was the first and most comprehensive effort to exploit the unique powers of polarimetry at wavelengths not visible on Earth. Before the development and flight of this experiment on this mission, virtually no such data existed because of the difficulty in obtaining these measurements with the degree of accuracy required for astronomical observations.[b] The Cassegrain-type telescope used its 50-cm (20-in) diameter f/10 mirror with an area of 1,800 cm^2 (279 sq in) to reflect UV light to a spectropolarimeter, where two rotating wheels were used to select the focal plane aperture and the polarimetry analyzer. The spectropolarimeter measured the degree and direction of polarization at many different wavelengths.

Table 4–81. Astro Mission Characteristics (Continued)

Instruments/Experiments[c]	• Broad Band X-ray Telescope (Astro-1 only) PI: Dr. Peter J. Serlemitsos, Goddard Space Flight Center The BBXRT obtained x-ray spectra covering the 0.3-keV to 10.0-keV band. It viewed high-energy objects such as active galaxies, quasars, and supernovas. It was mounted on a separate pointing system secured by a support structure in the cargo bay. For joint observations, the BBXRT was aligned with the UV telescopes to see the same objects, but it also could be pointed independently to view other x-ray sources. Ground controllers operated the BBXRT remotely. The BBXRT consisted of two coaligned telescopes with focal lengths of 3.8 m (12.5 ft) and diameters of 40 cm (15.7 in). Each telescope contained a thin-foil conical mirror assembly made of 118 curved, gold-plated aluminum reflectors and a segmented, cryogenically cooled lithium-drifted silicon spectrometer at the focal plane. The whole optical system provided a total collecting area of 765 cm^2 (118.6 sq in) at 1.5 keV, and 300 cm^2 (46.5 sq in) at 7 keV.[d]
Remarks[e]	These missions demonstrated the benefits of human interaction in on-orbit astronomy. Besides being able to position the orbiter most advantageously for observations, crew members also could manually acquire observation targets.

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[a] "UIT Technical Summary," *http://praxis.pha.jhu.edu/instruments/uit_info.html* (accessed August 25, 2005).

[b] "WUPPE Technical Summary," *http://praxis.pha.jhu.edu/instruments/wuppe_info.html* (accessed August 25, 2005). Also "The Wisconsin Ultraviolet Photo-Polarimeter Experiment," *http://praxis.pha.jhu.edu/instruments/wuppe.html* (accessed August 25, 2005).

[c] "The Astro-1 Mission," *http://praxis.pha.jhu.edu/astro1/astro1_mission.html* (accessed August 23, 2005).

[d] "BBXRT," NASA's HEASARC: Observatories, *http://heasarc.gsfc.nasa.gov/docs/bbxrt/bbxrt_about.html* (accessed August 25, 2005).

[e] "STS-67 Mission Archives," *http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-67.html* (accessed May 9, 2006).

Table 4–82. Astro-2 HUT Scientific Achievements

Category	Description
Intergalactic Medium	The HUT science team's highest priority science goal was to detect and measure the characteristics of the primordial intergalactic medium (IGM), a hypothesized gas thought to be spread throughout the universe between the galaxies. The science team succeeded in performing multiple observations of a faint, high redshift quasar, using it as a "background" source to shine through the IGM; absorption of the quasars light at the "right" UV "colors" would indicate the presence of this elusive component of the universe.
Active Galaxy Nuclei	The HUT was used to observe the active galaxy NGC 4151, which may harbor an obscured black hole in its nucleus. The object was known to be variable on week-to-month timescales, and it had also been observed during Astro-1, providing an important comparison. NGC 4151 was observed to be about five times brighter during Astro-2 than it was during Astro-1. A detailed comparison of the differences allowed an unprecedented view of the structure of the region close to the black hole. Time variability during periods as small as two days may also be present in the Astro-2 data.
Elliptical Galaxies	During Astro-1, although only one elliptical galaxy and one "galactic bulge" region of a spiral galaxy (thought similar to an elliptical galaxy in many regards) were observed sufficiently to constrain models of the stars producing the faint UV light in these galaxies, these observations provided breakthroughs in understanding. The first results for six elliptical galaxies from Astro-2 were used to confirm and extend the preliminary Astro-1 results.

Table 4–82. Astro-2 HUT Scientific Achievements (Continued)

Supernova Remnants	These were the expanding gaseous nebulae created by supernova explosions, which often remain visible for thousands of years. As these nebulae expanded, they heated normally invisible regions of interstellar gas and caused them to glow. They provided new information not only about the stars that exploded but also the interstellar medium. Very few of these objects, however, were observable in UV light because of intervening absorption by dust and gas in the plane of our galaxy.
	Early Astro-2 results reported new detections for two galactic supernova remnants. The remnant called “Puppis A” was detected throughout the HUT wavelength range, producing insight into a cosmic collision between the supernova blast wave and an interstellar cloud. Also, the HUT was used to detect emission from a young remnant called SN 1006, so called because Chinese astronomers observed the supernova in 1006 A.D. This was a “young” supernova remnant, and the HUT detection was the first UV observation of such a fast interstellar shock wave, estimated to be traveling at 3,000 km/s (close to 1,900 mi/s).
Hottest Stars	Several of the hottest young stars in the nearby galaxies, called the Magellanic Clouds, were observed to determine their temperatures, masses, and radii. In addition, the HUT provided unique information on the stellar winds from these most massive of stars. Included in these observations was the current candidate for the most massive single star, a star nearly 200 times the mass of our Sun.
Cataclysmic Variable Stars	Certain cataclysmic variables undergo occasional outbursts in which their brightness increases by factors of 100 or more. The time between outbursts was not regular but varied from two weeks to months. The cause of these outbursts and their effects on the stars was poorly understood. On Astro-2, HUT scientists observed the dwarf nova U Geminorum 185 days after an outburst, which was the farthest away from an outburst that the system had ever been observed. During Astro-1, the HUT had observed this binary star just 10 days after an outburst. The comparison showed the clearest evidence yet that the white dwarf star not only got heated during an outburst, but that this heating primarily affected only a portion of the white dwarf’s surface.
	Three bright novae were also available for observation in the month or so before the Astro-2 launch. These objects were still in their decline phase during the mission, and HUT observations of two objects had been reported, including a time sequence on one object. The HUT observations were used to determine the abundances of carbon, nitrogen, and oxygen in the expanding gaseous shells as well as the time variability of the emissions.

Table 4–82. Astro-2 HUT Scientific Achievements (Continued)

Symbiotic Stars	These objects were composed of two stars in the late stages of evolution orbiting each other at a distance similar to that of Earth from the Sun. One star was a hot white dwarf which irradiated its cooler red giant companion. Astronomers made far-UV observations of several symbiotic stars with both the HUT and WUPPE. They studied the effect of the hot star's intense UV radiation on the outer layers and stellar wind of the red giant star. This provided a unique perspective on the structure and evolution of red giant star atmospheres.
Solar System	HUT scientists observed the Jovian system for comparison with Astro-1 observations. This comparison permitted a better understanding of the importance of the changing solar input. (Astro-2 was near solar minimum, while Astro-1 was near solar maximum.) A coordinated observation of Jupiter's northern polar aurora between the HUT and the Hubble Space Telescope would provide unique information on the physical processes and excitation mechanisms in Jupiter's atmosphere and magnetosphere. The HUT also observed Venus and Mars. The atmospheres of these planets, although very different from each other in terms of density, were both dominated by carbon monoxide emissions. Comparison of the HUT observations would provide new insights into the atmospheres of Earth's nearest planetary neighbors.

Table 4–83. Spartan 201 Mission Characteristics

Mission/Date	SPARTAN 201-01: April 8, 1993 SPARTAN 201-02: September 13, 1994 SPARTAN 201-03: September 7, 1995 SPARTAN 201-04: November 19, 1997 SPARTAN 201-05: October 29, 1998
Description	Each mission released a free-flying, autonomous spacecraft from the Shuttle bay for up to approximately 45 hours to observe and investigate the heating of the solar corona and acceleration of the solar wind that originates in the corona.
Instruments/Experiments	• The Ultraviolet Coronal Spectrometer used UV emissions from neutral hydrogen and ions in the corona to determine the velocities of the coronal plasma within the solar wind source region, as well as the temperature and density distributions of protons. • The White Light Coronograph measured visible light to determine the density distribution of coronal electrons within the same regions. Because Earth's atmosphere interferes with emissions at these wavelengths, the measurements had to be made from space rather than from the ground.

Table 4–84. ORFEUS-SPAS Science Payload[a]

Instrument	Features
FUV	Coverage of the 90 nm–125 nm wavelength range; spectral resolution of 10,000; Microchannel Plate Detector with optimized spatial resolution
EUV	Coverage of the 40 nm–115 nm wavelength range; spectral resolution of 5,000; detection of individual photons
IMAPS	Coverage of 95 nm–115 nm wavelength range; spectroscopy of interstellar gas lines spectral resolution of about 240,000; sub-Doppler
SESAM	Carrier for optical samples to investigate degradation of surfaces and materials in space environment; 40 places for user-provided samples

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[a] "Space Shuttle Mission STS-51 Press Kit," July 1993, p. 46, *http://www.jsc.nasa.gov/history/shuttle/shuttle_pk/pk/Flight_057_sts-051_press_kit.pdf* (accessed August 26, 2005).

INDEX

A

Academic programs, 10, 14
Accelerometer, 959
  "Access to Space" study, 22, 80, 172
ACE-Able Engineering, Inc, 857
Active Cavity Radiometer Irradiance Monitor (ACRIM), 421, 480
Acuña, Mario H., 940, 945, 953, 956
Adamson, James C.
  STS-28, 360, 380
  STS-43, 363, 409
Adrastea, 711
Advanced Carrier Customer Equipment Support System, 223
Advanced Charged Couple Imaging Spectrometer (ACIS), 656, 657, 839, 840
Advanced Communications Technology Satellite (ACTS), 161, 252, 254, 366, 454
Advanced Composition Explorer (ACE), 140, 579, 604–5, 606, 607, 772, 781, 806–9
Advanced Concepts and Technology, Office of (Code C)
  budgets and funding for, 13, 33, 35, 89, 91, 94, 100
  organization of, 27–28, 29
  responsibilities of, 13
  Robot Operated Materials Processing Systems (ROMPS), 472
Advanced Concepts division (Office of Space Access and Technology), 29
Advanced Launch System (ALS), 77–78, 101
Advanced Launch Technology, 27, 94
Advanced Materials Center for the Commercial Development of Space, 389
Advanced Photovoltaic and Electronic Experiments (APEX), 146
Advanced Programs and Projects, 27, 74–79, 91, 98
Advanced Projects Office (Office of Space Flight), 31, 32, 193
Advanced Protein Crystal Growth (APCG), 465
Advanced Satellite for Cosmology and Astrophysics (ASCA), 579, 664–66, 769, 849–53
Advanced solid rocket motor, 34, 89, 93, 109
Advanced Space Technology, 789
Advanced Space Transportation, 89, 91, 100
Advanced Space Transportation office (Office of Aeronautics and Space Transportation Technology), 32
Advanced Space Transportation Technology, 90, 91, 94
Advanced Technology and Mission Studies (Office of Space Science), 585
Advanced Transportation Technology, 101
Advanced X-ray Astronomical Facility (AXAF)
  approval of, 576
  AXAF-I, 653
  AXAF-S, 653
  budgets and funding for, 653–54, 779
  Chandra (AXAF), 576, 579, 652, 655–57, 838–41
  characteristics, instruments, and experiments, 654–57, 838–41; Advanced Charged Couple Imaging Spectrometer (ACIS), 656, 657, 839, 840; High Energy Transmission Grating (HETG) spectrometer, 657, 839–40, 841; High Resolution Camera (HRC), 656, 657, 839, 840; High Resolution Mirror Assembly, 654, 656–57; Low Energy Transmission Grating (LETG) spectrometer, 657, 839–40; Science Instrument Module (SIM), 657
  deployment of, 579
  development of, 652, 653
  objective of, 589, 652–53
Advisory Committee on the Future of the U.S. Space Program, 204–5, 287, 564
Aero Corporation, 894, 897
AeroAstro, L.L.C., 860
Aerobraking, 697, 727–28, 738, 956, 959
Aerodynamic Coefficient Identification Package (ACIP), 381, 397, 405
Aerojet, 142, 143, 144, 158, 180
Aeronautical Research and Technology, Office of, 14
Aeronautics, Exploration, and Technology, Office of, 24, 26, 288
Aeronautics, Office of, 14
Aeronautics and Space Report of the President, 41
Aeronautics and Space Reports of the President, xxi
Aeronautics and Space Technology, Office of (Code R)
  appropriations and functional areas, 10
  management of, 27
  Shuttle payloads: OAST flyer, 163, 266, 370, 498; OAST-2 experiments, 162, 256, 367, 465; SHARE, 377
Aeronautics and Space Transportation Technology, Office of (Code R), 13, 14, 32, 181, 182
Aerosol Collector and Pyrolyser (ACP), 979
Aerospace Corporation
  Comprehensive Energetic Particle Pitch Angle Distribution/Source-loss Cone Energetic Particle Spectrometer (CEPPAD/SEPS), 873
  Solar, Anomalous and Magnetospheric Particle

Explorer (SAMPEX), 598
  sounding rocket program, 889, 900
  Space Sciences Department, 873
Aerospace Medicine Division, 212
Aero-Space Technology, Office of, 182
Aerospatiale, 743
Aerospike engines, 83, 86, 176, 177, 179, 182, 183, 184, 185
Aerothermal Instrumentation Package (AIP), 398, 405
Africa, 471, 688
Agencia Espacial Brasileira (AEB). *See* Brazil and Brazilian Space Agency (AEB)
Agenzia Spaziale Italiana (ASI). *See* Italy and Italian Space Agency (Agenzia Spaziale Italiana [ASI])
Ahvaz, Iran, 716
Air Force Maui Optical System (AMOS) calibration test, 239, 377, 379, 380, 383, 384, 386, 389, 391, 397, 399, 410, 412, 414, 423, 428, 432, 440, 450, 454, 466, 470, 472, 483
Air Force, U.S.
  Air Force Program-675 instruments, 402
  Atlas rockets as ICBMs, 42
  Combined Release and Radiation Effects Satellite (CRRES), 44, 72, 122, 579, 593, 615, 618–20, 767, 819–22
  Defense Satellite Communication Systems (DSCS) III satellites, 45, 122, 123, 124
  Delta ELVs, 50
  ELV launch services, 38
  GAS experiments, 499, 503
  Geophysics Laboratory, 418, 890
  GPS satellites, 50, 51, 136–40
  Haystack Radar, 439
  Launch Vehicles Office and, 27
  Medium Launch Vehicle II program, 45
  Miniature Sensor Technology Integration (MSTI), 147, 152
  Pegasus ELVs, 152
  Phillips Laboratory, Kirtland Air Force Base, 80, 175, 859
  RLV Technology program, 80
  satellites, 44, 152
  Small Launch Vehicle program, 55
  Space and Missile Systems Center, 499
  Space Radiation program, 619
  Space Shuttle experiments, 243, 483
  Space Systems Division, 421
  Space Test Program, 503
  Titan ELVs, 61, 62
Airborne Electrical Support Equipment, 242
Akebono satellites, 821
Akers, Thomas D.
  STS-41, 361, 390
  STS-49, 356, 364, 422, 424
  STS-61, 357, 367, 458, 459, 628
  STS-79, 371, 512
Alabama Space & Rocket Center, 406
Alaska, 603
Albion Jr. High, Strongsville, Ohio, 515
Alcantara, Brazil, 895–97
Aldrich, Arnold D., 24, 26, 205
Alena Spazio, 854
Alenia Aerospazio, 228, 310
Alice Springs, Australia, 906, 912, 913, 919
All Sky Monitor (ASM), 600, 602, 801, 802, 803
Allen, Andrew M.
  administrative positions, 30, 209
  STS-46, 364, 427
  STS-62, 367, 464
  STS-75, 370, 500
Allen, Lew, 622–23
Alliant Techsystems
  Delta ELVs, 51, 144
  Pegasus ELVs, 51, 150
  Taurus ELVs, 153
  X-33, 177, 184
Allied Signal, 171, 180
Alpha Magnetic Spectrometer (AMS), 276, 541
Alpha Particle Spectrometer (APS), 945
Alpha-particle, Proton and X-ray Spectrometer, 966
Altitude Sensor Package (ASP), 436
Altman, Scott D., 374, 538
Amalthea, 711
Amazon Rainforest, 388
American Association for Promotion of Space in China, 419
American Flight Echocardiograph (AFE), 385
American Institute of Aeronautics and Astronautics (AIAA), xxii, 451, 452, 547
American Loop Heat Pipe with Ammonia (ALPHA), 527
Ames Research Center
  Autonomous Operations System, 857
  Center of Excellence designation, 11
  Galileo, 701, 932, 933, 936
  Gamma-ray Spectrometer (GRS), 945
  GAS experiments, 540
  Lunar Prospector, 944
  mission area, 11
  Nephelometer (NEP), 709, 933
  OEX program, 405
  sounding rocket program, 905
  X-34, 82
Anderson, John, 936
Anderson, Michael P., 373, 536
Andes Mountains, 388, 428
Andoya, Norway, 882, 886, 893, 897, 904
Androgynous Peripheral Docking Assembly, 293, 299, 300, 301, 568
Andromeda galaxy, 639
Animals in space
  ethical care and use of, 232, 412
  payload accommodations, 230–32
  STS-40, 244, 404
  STS-48, 412
  STS-58, 255, 456
Antarctica, 906, 909, 911, 914, 916, 918, 919, 920, 922, 925
Antenna, 638, 641
Antimatter, 276, 541, 650
Apollo program
  Apollo 11, 260, 470, 477
  Apollo 13, 240

  Apollo Moon landers, 741
  Apollo-Soyuz Test Project, 264
  end of, 190
Applied Physics Laboratory, Johns Hopkins University
  Advanced Composition Explorer (ACE), 604, 605, 806
  balloon flights, 916, 920
  Energetic Particle and Ion Composition (EPIC) Investigation, 863
  Energetic Particles Detector (EPD), 935
  Near Earth Asteroid Rendezvous (NEAR), 715, 717, 939–40
  NEAR Mission Operations System Ground Segment, 715
  Science Data Center, 715
Applied Research Corporation, 826
Apt, Jay, 242, 356, 362, 399, 400
Apt, Jerome
  STS-47, 365, 429
  STS-59, 367, 467
  STS-79, 371, 512
Aquatic Research Facility (ARF), 506
Arcilesi, Charles J., 30
Arecibo Observatory, 722
Argentina and Argentinean National Commission of Space Activities
  Hard X-ray Spectrometer (HXRS), 860
  High Energy Transient Experiment (HETE), 147, 148, 576, 771
  Salyut space station, 299
  Satelite de Aplicaciones Cientifico-A (SAC-A), 164, 549
  Satelite de Aplicaciones Cientifico-B (SAC-B), 147, 148, 576, 671, 672, 771, 860–61
Ariane rocket, 38, 39, 279, 310
Arizona State University, 952, 955
Armstrong, Spence M., 181, 182
Army, Department of the, 902, 903
Army, U. S., 58, 321, 421
Arnold Air Force Base, 174
Array of Low Energy X-ray Imaging Sensors (ALEXIS), 146
Art Program, NASA, 477
Ascent Particle Monitor (APM), 389, 411
Asphalt Evaluation Experiment (AEE), 534
Assembly of Station by EVA Method (ASEM), 356, 424
"Assignment—The Stars" (Space Classroom Program), 397
Assisted Crew Return Vehicle, 290. *See also* Crew return vehicle
Association of Universities for Research in Astronomy, Inc. (AURA), 626
Assured Crew Return Vehicle, 101, 314, 320, 329, 341, 564
Asteroids
  asteroid 1992 KD, 668
  Eros, 715–16, 943
  Galileo and, 701, 705, 930, 937
  Gaspra, 705, 930, 937
  Geographos, 721, 722–23, 948, 951
  Ida, 705, 707, 930, 937
Astro-1
  characteristics, instruments, and experiments, 354, 395–96; Broad Band X-ray Telescope (BBXRT), 395, 396, 751, 753, 756, 849, 983; Hopkins Ultraviolet Telescope (HUT), 396, 750–51, 752, 981; Ultraviolet Imaging Telescope (UIT), 396, 750–51, 752, 982; wide field cameras (WFCs), 396, 750–51; Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), 750–51, 753, 982
  deployment of, 159, 242, 362, 750–51, 774, 981; delay of, 575
  development of, 750–51
  Diffuse X-ray Spectrometer (DXS), 756
  discoveries and scientific contributions from, 751–53, 984, 986
  objective of, 774
Astro-2
  Broad Band X-ray Telescope (BBXRT), 754
  characteristics, instruments, and experiments, 262–63, 264, 354, 485; Hopkins Ultraviolet Telescope (HUT), 485, 754–55, 981, 984–86; Ultraviolet Imaging Telescope (UIT), 485, 486, 754, 982; Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), 485, 754, 982, 986
  deployment of, 369, 775, 981
  discoveries and scientific contributions from, 984–86
  guest investigators, 754
  objective of, 775
  sounding rocket program and, 691
ASTROCULTURE, 425, 450, 461, 495, 536, 542
Astro-D, 664, 769. *See also* Advanced Satellite for Cosmology and Astrophysics (ASCA)
Astronaut Candidate Program, 232, 234
Astronaut Office, 233
Astronaut Science Advisor (ASA), 456
"Astronomical Advantages of and Extra-terrestrial Observatory" (Spitzer), 620
Astronomical Institute, 763
Astronomical Research for Origins and Planetary Systems Division (Office of Space Science), 584, 585
Astronomical x-ray sources, 575
Astronomy and Aerophysics Survey Committee (AASC), 658–59
Astronomy exploration, 577, 578, 584
Astronomy Survey Committee, National Academy of Sciences, 613
Astrophysics Division (Office of Space Science), 582, 583, 584, 589
Astrophysics Division (Office of Space Science and Applications), 581, 582
Astrophysics missions, 242, 578, 589, 767, 768, 769, 770, 771, 773
ASTRO-Shuttle Pallet Satellite (ASTRO-SPAS), 253, 269, 762–63. *See also* Cryogenic Infrared Spectometers and Telescopes for the Atmosphere-Shuttle Pallet Satellite (CRISTA-SPAS); Orbiting and Retrievable Far and Extreme Ultraviolet Spectograph-Shuttle Pallet Satellite (ORFEUS-SPAS)

  Student Experiment on ASTRO-SPAS (SEAS), 766
Astro-Space Division, General Electric Company
  Mars Observer, 952
  Space Station development, 200, 281, 288, 552, 564
Asuka, 769. *See also* Advanced Satellite for Cosmology and Astrophysics (ASCA)
Athena ELVs
  Athena I, 41, 42, 120
  Athena II, 20, 41, 42, 121, 718
  characteristics of, 41, 42, 120–21
  launches with, 21, 38, 40, 41–42, 118, 119, 718, 944
  success rate for launches, 38, 118
ATK Thiokol Propulsion Company, 51
Atlantic Canada Thin Organic Semiconductors (ACTORS), 507, 543
Atlantis (OV-104)
  characteristics of, 217–18, 350
  hail damage, 392
  hydrogen fuel leak, 392, 420
  Kennedy Space Center landing, first, 392
  launch vehicle function of, 20
  Mir support missions and, 220–21
  missions flown with, 159–60, 162–64
  Orbiter Docking System, 220
  Orbiter Maintenance Down Period (OMDP), 220–21, 479
  oxygen leak, 420
  STS-30, 159, 239, 379; IUS launch, 72, 75; Magellan deployment, 72, 75, 159, 239, 360, 379, 693–94, 767, 927
  STS-34, 159, 168, 239, 382–83; Galileo deployment, 159, 239, 360, 382, 383, 703, 767, 930, 932
  STS-36, 159, 240, 387, 395
  STS-37, 159, 242, 356, 399–400, 645, 833
  STS-38, 159, 242, 392–93
  STS-43, 160, 168, 244, 409–10
  STS-44, 160, 168, 244, 413–14, 522
  STS-45, 160, 246, 420–21
  STS-46, 160, 247–48, 427–28; EURECA, 247, 252, 253, 427, 428; TSS deployment, 74, 427, 428
  STS-66, 162, 260–61, 479–81
  STS-71, 162, 263–64, 487–88, 491; Shuttle-*Mir* program, 300, 301, 302, 555
  STS-74, 266, 496–97; Shuttle-*Mir* program, 300–301, 496, 497, 555
  STS-76, 163, 266–67, 355, 358, 502–4; Shuttle-*Mir* program, 502, 504, 555
  STS-79, 163, 268, 355, 512–13, 514, 555
  STS-81, 163, 269, 355, 517–18, 555
  STS-84, 164, 270, 355, 523–24, 555
  STS-86, 164, 272, 273, 355, 531–32, 555
Atlas ELVs
  acquisition of, 37
  Atlas E: characteristics of, 127; development of, 43; launches with, 43, 44, 118, 122, 123, 124; management of, 29
  Atlas G Centaur: characteristics of, 128; development of, 43, 70, 72; launches with, 43, 44, 118, 122, 619, 666, 854
  Atlas I, 29, 43, 44–45, 118, 122–25, 129
  Atlas II, 20, 43, 45–47, 122–26, 131
  Atlas IIA, 43, 45, 46, 118, 123–26, 132
  Atlas IIAS: characteristics of, 47, 133–34; launches with, 43, 45, 46–47, 118, 123–26, 681; management of, 29
  Atlas IIIA, 20
  characteristics of, 43–47
  development of, 42–43
  ICBM use of, 42
  launches with, 19, 21, 38–40, 118, 122–26, 767; event sequence for geosynchronous mission, 44, 130; Shuttle launch and, 494, 514
  management of, 29
  naming conventions, 43
  payloads launched from, 122–26
  success rate for launches, 38, 46, 118
Atmosphere Structure Instrument (ASI), 708–9, 933
Atmospheric & Environmental Research, Inc., 936
Atmospheric Laboratory for Applications and Science (ATLAS)
  ATLAS-1, 160, 246, 354, 364, 420–21
  ATLAS-2, 161, 250, 365, 441
  ATLAS-3, 162, 260–61, 368, 479, 480
Atmospheric Reentry Demonstration, 310
Attached pressurized module, ESA, 284, 285, 286
Augustine, Norman R., 25, 78, 204–5, 287, 564
Auroral Photography Experiment (APE), 384, 409, 454, 466
Auroral Photometer (AP), 810
Auspace, Ltd., 419, 486
Austin, Gene, 178, 183
Australia
  Australian Space Office, 419, 486
  Deep Space Network (DSN) station, 666, 682, 686, 701
  International Solar-Terrestrial Physics (ISTP) program, 672
  IUE observers, 688
Austria, 672
Authorization and appropriation bills
  Discovery Program, 714
  human spaceflight, funding for, 212
  influence of on direction of NASA, 3
  launch systems, funding for, 33–34, 36, 37, 77, 89–90
  NASA, funding for, 7
  space science missions, 587, 587n38, 588
  Ulysses, 660
Automated Transfer Vehicle, 279, 309–10, 568
Autonomous Operations System, 857
Autonomous Optical Navigation, 857

B

Bagenal, Frances, 936
Bagian, James P.
  STS-29, 360, 376
  STS-40, 362, 403
Bahcall, John, 658

Bahcall Committee, 658–59
Bahcall Report, 658–59
Baikonur Cosmodrome, Kazakhstan, 315, 735
Baker, Ellen S.
    STS-34, 360, 382
    STS-50, 364, 425
    STS-71, 369, 487
Baker, Michael A.
    STS-43, 363, 409
    STS-52, 365, 435
    STS-68, 368, 476
    STS-81, 371, 517
Baking Bread in Space, 434
Ball Aerospace & Technologies, 659
Ball Aerospace Systems Goup, 819, 824, 829, 831
Ball Electro-Optics & Cryogenics Division, 627, 829
Ballistic Missile Defense Organization (BMDO)
    Clementine, 720, 724
    DC-X program, 80, 172
    Miniature Sensor Technology Integration (MSTI), 152, 668
    Pegasus ELVs, 55
    Single Stage Rocket Technology program, 80
    Strategic Defense Initiative Organization, 720
Balloon flights, 693, 694, 906–25
Balmino, Georges, 927
Balogh, Andrew, 844
Banjul, The Gambia, 237
Baroreflex (BA), 446–48
Barry, Daniel T., 358, 370, 498, 499
Barth, Charles, 810
Batelle, 389
Battlefield Laser Acquisition Sensor Test (BLAST), 439
Beacon Monitor Operations, 857
Beijing Institute of Environmental Engineering, 473
Bekey, Ivan, 29
Belen Jesuit Preparatory School, Miami, Florida, 543
Belgium
    ATLAS-1 instruments, 246
    ESA membership, 279
    International Solar-Terrestrial Physics (ISTP) program, 672
    SOLCON, 480
Bell Laboratories, Lucent Technologies, 846, 933, 934
Bellarmine College, Louisville, Kentucky, 529, 547
Belton, Michael J., 934
Ben Guerir, Morocco, 237
BeppoSAX satellite, 125, 578, 643, 650, 666, 771, 854–55
BeppoSAX Science Data Center, 666
Bernhardt, Paul, 820
Bertaux, Jean Loup, 876
Bertotti, Bruno, 848
B.F. Goodrich, 181, 182, 183
Big Bang
    age of universe, 641
    COBE and, 593, 791, 792
    FUSE mission and, 613, 614
    HUT and, 755
    theory of, 593, 595, 791–92
Binder, Alan, 945
Binns, Walter, 806
Biological Research in Canister (BRIC), 472, 477, 483, 490, 492, 506, 511, 515, 529, 547
Biomedical experiments, 243–44, 331
Bioprocessing Modules (PBM), 442
Biorack, 258, 259, 267, 524
Bioreactor Demonstration Systems (BDS), 466, 490, 529, 540
Bioreactor Flow and Particle Trajectory (BFPT), 414
Bioserve/Instrumentation Technology Associates Materials Dispersion Apparatus (BIMDA), 399, 410
Bird, Michael K., 847, 978
Bistatis Radar Experiment, 950
Black Brant sounding rocket, 692
Black holes
    Advanced Satellite for Cosmology and Astrophysics (ASCA), 852
    Advanced X-ray Astronomical Facility (AXAF), 652–53
    Hubble Space Telescope data, 637, 640
    RXTE and, 599, 803
Blaha, John E.
    aboard *Mir*, 268, 269, 512, 517, 555
    STS-29, 360, 376
    STS-33, 360, 384
    STS-43, 363, 409
    STS-58, 366, 455
    STS-79, 371, 512
    STS-81, 269, 371, 517
Blake, J. Bernard, 873
Blamont, Jacques E., 958
Bless, Robert C., 828
Bloomfield, Michael J., 373, 531
Blue Mountain High School, Floyd, Virginia, 548
Bluford, Guion S., Jr.
    STS-39, 362, 401
    STS-53, 365, 438
Bochsler, Peter, 806
Boeing Company/Boeing Aerospace/Boeing Defense and Space Group
    Advanced Launch System (ALS), 78
    aerospike engines, 185
    Boeing North America, 65n69
    inertial upper stage (IUS), 167
    Power Activation and Switching Module, 859
    Space Shuttle modifications and upgrades, 220
    Space Station: assembly schedule, 306, 557; construction of components, 308–9, 568; contract for, 296, 304, 307, 567, 568; Cost Control Task Force, 214, 314, 569, 570; costs and overruns, 214, 313; development of, 191, 199, 208, 281, 552, 564, 566; termination of *Freedom*, 304
    VentureStar, 182
Bolden, Charles F., Jr.
    STS-31, 361, 388
    STS-45, 364, 420

  STS-60, 367, 460
Bondar, Roberta L., 245, 363, 415
Bonn University, 933
Booker T. Washington Senior High School, Houston, Texas, 418
Boost Guidance System, S-19, 692
Boston University
  balloon flights, 906, 911
  Center for Space Physics, 873
  Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE), 873
  sounding rocket program, 882, 886, 888, 889, 902, 904, 905
  Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources (TERRIERS), 592, 593
Botswana, 388
Bougeret, J. L., 867
Bowersox, Kenneth D.
  STS-50, 364, 425
  STS-61, 367, 458, 459
  STS-73, 369, 494
  STS-82, 372, 519
Bowyer, Stuart, 793
Box Elder High School, Brigham City, Utah, 543
Boy Scout Troop 177, Gambrills, Maryland, 544
Boynton, William V., 953, 970
Brady, Charles E., Jr., 371, 508
Bragg Crystal Spectrometer (BCS), 684, 755, 880
Brand, Vance D., 362, 394
Brandenstein, Daniel C.
  STS-32, 361, 385
  STS-49, 364, 422, 424
Brandt, John C., Jr., 827
Branscome, Darrel, 32
Brazil and Brazilian Space Agency (AEB)
  balloon flights, 921, 922
  ICBC during STS-46, 428
  imaging of during STS-59, 256
  International Space Station (ISS): contributions to, 280, 311, 569; development of, 191, 277
BREMEN Satellite (BREMSAT), 463
Brevard Community College, Cocoa, Florida, 543
Brice, Neil, 820
Briggs, Geoffrey, 581
Brilliant Eye Ten-Kelvin Sorption Cryocooler Experiment (BETSCE), 506
Brinkley, Randy, 209, 210
Brinkman, S. C., 840
Brinton, Henry, 584
British Science and Engineering Research Council (Particle Physics and Astronomy Research Council), 687
British Sugar PLC, 507
Broad Band X-ray Telescope (BBXRT)
  Astro-1, 395, 396, 751, 753, 756, 849, 983
  Astro-2, 754
Broward Community College, Davie, Florida, 543
Brown, Curtis L., Jr.
  STS-47, 365, 429
  STS-66, 368, 479
  STS-77, 370, 505
  STS-85, 373, 528
  STS-95, 374, 545
Brown, Mark N.
  STS-28, 360, 380
  STS-48, 363, 411
Brown, Robert H., 977
Brown University, 924
Brueckner, Guenter, 876
Bruno B. Rossi X-ray Timing Explorer, 599. *See also* Rossi X-ray Timing Explorer (RXTE)
Bubble Data Recorder (BDR), 684, 685
Buchli, James F.
  STS-29, 360, 376
  STS-48, 363, 411
Buckey, Jay C., 374, 538
Budarin, Nikolai, 487
Budgets and funding
  annual budget estimates, xxi, 37, 96–117, 574
  appropriations categories, 6, 12–15
  authorization and appropriation bills: Discovery Program, 714; human spaceflight, funding for, 212; influence of on direction of NASA, 3; launch systems, funding for, 33–34, 36, 37, 77, 89–90; NASA, funding for, 7; space science missions, 587, 587n38, 588; Ulysses, 660
  for Centers, 6
  for crew return vehicle, 320
  for Discovery Program, 587, 714, 788
  full-cost accounting, xxi, 7–8, 214–15, 586–87
  for GAS program, 212
  for Hitchhiker program, 212
  for human spaceflight programs, 189–90, 212–15, 324–48
  for launch systems, 33–37, 89–117
  for NASA, 5–8, 33–34, 212
  programmed budget, 36, 91–95
  for programs and projects, 5
  for space science missions, 585–88, 776–89
  for Space Shuttle program, 30, 33–36
  for Space Station program: *Alpha*, 191, 208, 296; *Freedom*, 191, 208, 281–84, 287–88, 290, 293–96, 552, 565, 566; funding history, 333–43; Human Space Flight (HSF) appropriations, 35, 213–15, 324–26; ISS, 305, 312, 313–14, 568, 570; Programmed Budget, 327–30; Science, Aeronautics, and Technology (SAT) appropriations, 213–15; Space Transportation Capability Development appropriations, 34; Spaceflight, Control, and Data Communications (SFC&DC) appropriations, 6, 15
Bundesministeriium für Forschung und Technologie (BMFT [Federal Ministry for Research and Technology]), 615
Bunner, Alan, 584
Burlaga, Leonard, 806
Bursch, Daniel W.
  STS-51, 366, 453
  STS-68, 368, 476
  STS-77, 370, 505
Burst and Transient Source Experiment (BATSE), 645, 646, 647–48, 649–50, 834, 837

Bush, George H. W.
  Endeavour, naming of, 218
  NASA organization, 24
  Space Exploration Initiative, 576–77
  space policy of, 3, 21–22
  Space Station *Freedom*, 290, 565
  U.S.-Russian Cooperative Program, 291, 292, 565
Business Management office (Office of Space Flight), 31, 32, 193

C

Cabana, Robert D.
  Shuttle Training Aircraft, 487
  STS-41, 361, 390
  STS-53, 365, 438
  STS-65, 367, 469
  STS-71, 487
  STS-88, 317, 374, 549
California Deep Space Network (DSN) station, 701
California Institute of Technology
  Advanced Composition Explorer (ACE), 605, 806, 807
  balloon flights, 906, 916, 919, 922, 925
  Galileo, 936
  GAS experiments, 506
  Heavy Ion Counter (HIC), 935
  Jet Propulsion Laboratory staffing, 4
  SIRTF Science Center, 660
  Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX), 598, 797, 798
  sounding rocket program, 901, 903, 905
  Space Radiation Laboratory, 806
  Wide Field and Planetary Camera (WFPC), 824; WFPC2, 829
California State University, Northridge (CSUN), 406, 462
Calle, Chris, 477
Calle, Paul, 477
Callisto, 710, 711, 712, 931
Cameron, Kenneth D.
  STS-37, 362, 399
  STS-56, 365, 441
  STS-74, 370, 496
Camp Tortuguero, Puerto Rico, 890, 904–5
Canada and Canadian Space Agency (CSA)
  astronauts on STS-74, 266
  Canadian Astronomical Data Centre, 687
  CANEX-2, 436
  Commercial Float Zone Facility, 267
  Configurable Hardware for Multidisciplinary Projects in Space (CHAMPS), 452
  Far Ultraviolet Spectroscopy Explorer (FUSE), 613, 615
  GAS experiments, 434, 475, 507, 543
  International Microgravity Laboratory (IML-2), 470
  International Solar-Terrestrial Physics (ISTP) program, 672
  International Space Station (ISS): agreements governing, 314–15, 569; contributions to, 279, 305, 306, 316, 319, 556; development of, 191, 277
  Life and Microgravity Spacelab (LMS), 268, 509–11
  Microgravity Sciences Program, 543
  Mobile Servicing Systems training, 200
  Neurolab mission, 274
  payloads launched for, 21
  remote sensing satellite, 40, 139
  Space Station *Alpha*, 297
  Space Station *Freedom*: components for, 281; contributions to, 284–85, 289; development of, 190, 280
Canadian Protein Crystallization Experiment (CAPE), 531
Canary Islands, Spain, 55
Canberra, Australia, 666, 682, 686
CAN-DO (Charleston County School District, Charleston, South Carolina), 451, 515, 530, 544
Canizares, Claude R., 841
Cape Canaveral Air Force Station, Florida, launches
  ACE, 806
  Athena ELVs, 42
  BeppoSAX, 578, 666, 854
  Cassini-Huygens, 971
  CRRES, 819
  Deep Space 1/SEDSAT, 856
  EUVE, 596, 793
  Geotail satellite, 862
  Mars Climate Orbiter, 738, 967
  Mars Observer, 952
  Mars Polar Lander, 969
  NEAR, 939
  payload characteristics for ELVs, 41
  Pegasus ELVs, 55
  ROSAT, 816
  RXTE, 801
  SOHO, 875
  Titan ELVs, 61
  Wind, 866
Cape Canaveral, Florida, 21. *See also* Kennedy Space Center
Capillary Pumped Loop (CPL), 462, 492, 515, 547
Carl Sagan Memorial Station, 731
Carl Zeiss Company, 615
Carlson, Charles W., 804–5
Carlson, RObert, 934
Carnegie Mellon University, 857
Carpenter, Joyce, 209
Carter, Manley L., Jr., 360, 384
Casper, John H.
  STS-36, 361, 387
  STS-54, 365, 440
  STS-62, 367, 464
  STS-77, 370, 505
Cassini, Jean-Dominique, 740
Cassini Plasma Spectrometer (CAPS), 973
Cassini-Huygens
  approval of, 576
  budgets and funding for, 740, 741, 787
  characteristics, instruments, and experiments, 741–44, 745, 971–79; Cassini Plasma Spec-

trometer (CAPS), 973; Composite Infrared Spectrometer (CIRS), 973–74; Cosmic Dust Analyzer (CDA), 973; Duel Technique MAG, 975; Imaging Science Subsystem (ISS), 974; Ion and Neutral Mass Spectrometer (INMS), 974; Magnetospheric Imaging (MIMI) Mass Spectrometer, 975; Radio and Plasma Wave Science (RPWS) instrument, 976; Radio Detection and Ranging (RADR) instrument, 975; Radio Science Subsystem (RSS), 976; Radioisotope Thermoelectric Generators (RTGs), 741–42; Ultraviolet Imaging Spectrograph (UVIS), 977; Visual and Infrared Mapping Spectrometer (VIMS), 977
  deployment of, 61, 63, 156, 742, 772
  development of, 739, 740–41, 742
  discoveries and scientific contributions from, 974, 976
  Huygens science probe, 739, 741, 743; Aerosol Collector and Pyrolyser (ACP), 979; Descent Imager/Spectral Radiometer (DISR), 978; Descent Module, 743; Doppler Wind Experiment (DWE), 978; Entry Assembly, 743; Gas Chromatograph Mass Spectrometer (GCMS), 979; Huygens Atmospheric Structure Instrument, 978; Permittivity and Electromagnetic Wave Analyzer, 978; probe support equipment, 743; Surface-science Package (SSP), 979
  naming of, 740
  objectives of, 772, 971–72
  trajectory and orbits of, 742, 743
CCM-A, 515, 532
Celestial Mechanics, Jet Propulsion Laboratory (JPL), 936
Cement Mixing Experiment (CME), 534
Centaur upper stage, 70, 71, 72, 73, 167
Center for Commercial Development of Space (CCDS), NASA
  Protein Crystal Growth (PCG) experiments, 378
  Protein Crystallization Facility (PCF), 423
  Robot Operated Materials Processing Systems (ROMPS), 472
  SPACEHAB experiments, 252, 460
Center for Macromolecular Crystallography (CMC), 378, 423
Center for Physics and Astronomy, Johns Hopkins University, 613
Center for Space Physics, Boston University, 873
Center for Space Transportation and Applied Research (CSTAR), 48–49
Centers of Excellence, 4, 11, 583–84. *See also specific centers*
Centre de Recherches en Physique de l'Environment, 936
Centre d'Etude Spatiale des Rayonnements (CESR), 861
Centre National d'Etudes Spatiales (CNES). *See* France and French Space Agency (Centre National d'Etudes Spatiales [CNES])
CFI, 178
Chabrow, Jay, 214, 314, 570
Challenger
  accident, 20, 190
  changes following accident, 64, 616
  delays following accident, 575, 577, 621, 661, 693, 702, 750–51, 756
  ELV use following, 21, 49, 61, 72, 594, 616, 619
  HiRAP, 397
  launch vehicle function of, 20
  replacement for, 217
  return to flight following accident, 190
  safety emphasis following accident, 70, 190
Chandra (AXAF), 576, 579, 652, 655–57, 838–41
Chandra Operations Control Center, 657
Chandra X-ray Center (CXC), 657
Chandrasekhar, Subrahmanyan, 654–55
Chang-Diaz, Franklin R.
  STS-34, 360, 382
  STS-46, 364, 427
  STS-60, 367, 460
  STS-75, 370, 500
  STS-91, 374, 541
Characterization of Neurospora Circadian Rhythms (CNCR), 385
Charge, Element, and Isotope Analysis System (CELIAS), 877
Charge and Mass Magnetospheric Ion Composition Experiment (CAMMICE), 873
Charge Coupled Device (CCD) camera system, 851
Charge Coupled Device (CCD) detectors, 610, 664, 665, 849
Charged Particle Measurements Experiment, 686
Charged Particle Telescope (CPT), 948
Charleston County School District, Charleston, South Carolina (CAN-DO), 451, 515, 530, 544
Chawla, Kalpana, 373, 533
Cheli, Maurizio, 370, 500
Chemical Gardens Experiment, 434
Chemical Precipitate Formation, 407
Chemical Release Module (CREM), 619
Chemical Release Observation (CRO), 402
Chemical Unit Process (CUP), 543
Chenette, David L., 874
Cheng, Andrew F., 936
Chernomyrdin, Viktor, 297, 298, 566, 567
Chesapeake Bay Girl Scout Council, Salisbury, Maryland, 544
Chiao, Leroy
  STS-65, 367, 469
  STS-72, 358, 370, 498, 499
Chief Financial Office, Office of, 190, 574
Chile, 622
Chilton, Kevin P.
  administrative positions, 210
  STS-49, 364, 422
  STS-59, 367, 467
  STS-76, 370, 502
China, 688
Chinese Academy of Sciences, Beijing, 537
Chinese Society of Astronautics, 419
Chretien, Jean-Loup J.M., 373, 531

Christensen, Philip R., 952, 955
Christian, Carol, 793
Chromosome and Plant Cell Division in Space Experiment (CHROMEX), 377, 390, 440, 454, 477, 483
Clarkson University Potsdam, New York, 472
Cleave, Mary L., 360, 379
Clementine, 156, 720–24, 769, 948–51
Clemson University, 889, 890, 894, 896, 898, 900, 904
Clervoy, Jean-Francois
  STS-66, 368, 479
  STS-84, 372, 523
Clifford, Michael R.
  STS-53, 365, 438
  STS-59, 367, 467
  STS-76, 358, 370, 502, 504
Cline, T, L,, 869
Clinton, William J.
  communication with Shuttles, 252, 488
  funding for NASA programs, 36, 191, 208
  Living With a Star initiative, 580
  missile technology to India, 297
  National Space Transportation Policy, 172
  Shuttle launch attendance, 548
  space policy of, 3, 22–23, 80
  Space Station program, 191, 208, 213, 293–97, 565–66
  United States-Russian Commission, 297
Closed Equilibrium Biological Aquatic System (CEBAS), 536
Cloud Logic to Optimize Use of Defense System (CLOUDS), 380, 384, 402, 421, 439
Cluster spacecraft, 579, 672, 676
Coats, Michael L.
  STS-29, 360, 376
  STS-39, 362, 401
Cockrell, Kenneth D.
  dogtag, 265
  STS-56, 365, 441
  STS-69, 265, 369, 491
  STS-80, 371, 514
Code, Arthur D., 982
Code of Federal Regulations, 222–23
Colegio Santa Hilda, Buenos Aires, Argentina, 548
Coleman, Catherine G., 369, 494
Collaborative Solar-Terrestrial Research (COSTR) program, 672, 673
Collaborative Ukrainian Experiment (CUE), 534
Collier, James, 211
Collins, Eileen M.
  STS-63, 261, 368, 482
  STS-84, 372, 523
Collisions into Dust Experiment (COLLIDE), 540
Colorado Space Grant Consortium, 440, 895
Columbia (OV-102)
  AIP, 398
  characteristics of, 217–18, 350
  days in space for orbiter, 251
  extended duration orbiter, 470, 495, 511, 522, 527, 540
  fuel cell, concern about, 521, 522
  hinges from, 401
  HiRAP, 397
  hydrogen fuel leak, 392, 394, 395, 403, 435, 494
  launch vehicle function of, 20
  Mir support missions and, 220
  missions flown with, 159–64
  modifications and upgrades to, 219–20, 258, 425
  network signal processors, 538
  Orbital Flight Test missions (STS-1 through STS-5), 398
  Orbiter Maintenance Down Period (OMDP), 220, 494
  oxygen leak, 444
  oxygen transducer replacement, 403
  SILTS, 386, 397, 405
  STS-1, 398
  STS-2, 398
  STS-3, 398
  STS-4, 219, 222, 398
  STS-5, 219, 398
  STS-9, 191, 219
  STS-28, 159, 239, 380–81
  STS-32, 159, 240, 385–86, 397, 405
  STS-35, 159, 242, 392, 394–98, 405, 756, 774, 981
  STS-40, 160, 219, 243–44, 397, 403–8
  STS-50, 160, 247, 425–26
  STS-52, 161, 249, 435–37
  STS-55, 161, 238, 250–51, 444–48
  STS-58, 161, 255, 455–57
  STS-62, 162, 256, 464–66
  STS-65, 162, 258–59, 469–70
  STS-73, 163, 265, 494–95
  STS-75, 75, 163, 266, 500–501
  STS-78, 163, 268, 508–11
  STS-80, 163, 269, 514–16
  STS-83, 163, 270, 521–22, 525
  STS-87, 164, 272, 274, 276, 359, 533–35, 759–60, 775
  STS-90, 164, 227, 274–75, 538–40
  STS-94, 164, 270, 522, 525–27
Columbia University
  balloon flights, 921, 922
  sounding rocket program, 885, 901
Columbus Orbital Facility, 279, 280, 305, 309, 310, 313, 556, 558, 568
Combined Release and Radiation Effects Satellite (CRRES), 44, 72, 122, 579, 593, 615, 618–20, 767, 819–22
Combustion Module (CM), 521, 526
Comet Nucleus Tour (CONTOUR), 715, 938
Comet Rendezvous Asteroid Flyby (CRAF), 576, 739–40, 741, 787
Comets
  Giacobini-Zinner comet, 575, 591
  Hale-Bopp comet, 529, 662, 680
  Halley's Comet, 750, 751, 824
  Kopff comet, 739
  missions to explore, 575
  Shoemaker-Levy 9 comet, 634, 635, 706, 707, 717, 930, 937

Commercial Development division (Office of Space Access and Technology), 29
Commercial Float Zone Facility, 267
Commercial General Bioprocessing Apparatus (CGBA), 268, 440, 465, 483, 492
Commercial launch license, 48
Commercial Materials Dispersion Apparatus Instrument Technology Associates Experiments (CMIX), 436, 442, 486, 492, 515
Commercial Middeck Augmentation Module (CMAM) contract, 227, 460
Commercial Processing experiments, 406
Commercial Programs, Office of (Code C), 9, 27, 227, 378
Commercial Protein Crystal Growth (CPCG) experiments, 423, 437, 454, 465, 470, 477, 490, 498, 501, 532, 542
  CPCG-VDA (Vapor Diffusion Apparatus), 483
Commercial Refrigerator Incubator Module (CRIM), 423
Communication Division (Office of Space Flight), 32
Communications and Information Sciences Division (Office of Space Science and Applications), 581
Communications Research Centre of Canada, 900
Components, systems, and modules, 280, 569
Composite Infrared Spectrometer (CIRS), 973–74
Comprehensive Energetic Particle Pitch Angle Distribution/Source-loss Cone Energetic Particle Spectrometer (CEPPAD/SEPS), 679, 680, 873
Comprehensive Plasma Investigation (CPI), 862
Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP), 877
Compton, Arthur Holly, 645
Compton Gamma Ray Observatory (CGRO)
  boosts to higher orbits, 651
  characteristics, instruments, and experiments, 243, 644, 645, 646, 647, 833–37; Burst and Transient Source Experiment (BATSE), 645, 646, 647–48, 649–50, 834, 837; Compton Telescope (COMPTEL), 645, 646, 648, 835, 836; Energetic Gamma Ray Experiment Telescope (EGRET), 645, 646, 648, 834, 835, 836; high-gain antenna, 242, 400, 647; Oriented Scintillation Spectrometer Experiment (OSSE), 645, 646, 650, 834, 836
  deployment of, 159, 242, 356, 362, 399, 578, 645, 768, 833
  development of, 645, 646
  discoveries and scientific contributions from, 647–50, 836–37
  funding for, 778
  naming of, 645
  objectives of, 578, 589, 644, 646–47, 768, 833
  orbit of, 651
  reentry, controlled, 651
  sounding rocket program and, 691
Compton Telescope (COMPTEL), 645, 646, 648, 835, 836
Computer (Compact) Disc Evaluation Experiment (CDEE), 534
Conestoga ELVs
  characteristics of, 20, 135
  development of, 47–48
  launches with, 21, 38, 40, 47–49, 118
  success rate for launches, 38, 118
Configurable Hardware for Multidisciplinary Projects in Space (CHAMPS), 452
Configuration Budget Review Team, 283, 564
Configuration Stability of Fluid Experiment (CSFE), 534
Congress, United States
  Advanced X-ray Astronomical Facility (AXAF), funding for, 653, 654
  authorization and appropriation bills: Discovery Program, 714; human spaceflight, funding for, 212; influence of on direction of NASA, 3; launch systems, funding for, 33–34, 36, 37, 77, 89–90; NASA, funding for, 7; space science missions, 587, 587n38, 588; Ulysses, 660
  Cassini funding, 741
  commercial and private sector development of launch systems, 21–22
  crew return vehicle, funding for, 320
  Endeavour, authorization to construct, 218
  funding for NASA's activities, 5, 6–7, 215n42
  House and Senate science committees, 7
  influence of on direction of NASA, 3, 4
  space science missions, funding for, 586, 587
  Space Station program: cancellation attempts, 296, 305, 306, 567, 568; funding for, 213, 214, 281–84, 287–88, 290, 296, 305, 307, 312, 564, 565, 566, 567, 568
Congressional Research Service, 190, 574
Consortium for Commercial Crystal Growth, Clarkson University, 472
Consortium for Materials Development in Space Complex Autonomous Payload (CONCAP)
  CONCAP II, 428
  CONCAP III, 428
  CONCAP IV, 257, 450, 468, 492
Construction of Facilities (C of F) appropriations, 6, 214, 215
Construction of Facilities funding history, 109
Cooke, Douglas, 210
Cooperative Astrophysics and Technology Satellite (CATSAT), 592, 593
Cooperative Solar Array (CSA), 497
Cornell University
  Galileo, 936
  Multispectral Imager (MSI), 939–40
  Near Infrared Spectrometer (NIS), 940
  sounding rocket program, 882, 885, 886, 890, 892, 897, 899, 904, 905
  Spitzer Space Telescope (Space Infrared Telescope Facility [SIRFT]), 659
Coronal Diagnostic Spectrometer (CDS), 875
Coronal-Sounding Experiment (SCE), 847
Corrective Optics Space Telescope Axial Replacement (COSTAR) system, 357, 459, 627–28, 829
Cosmic and Solar Gamma-burst Spectrometer, 966
Cosmic Background Explorer (COBE), 593–95,

596, 691, 767, 790, 791–92
Cosmic collision, 634, 635
Cosmic Composition Explorer, 604–5. *See also* Advanced Compostion Explorer (ACE)
Cosmic Dust Aggregation (CODAG), 547
Cosmic Dust Analyzer (CDA), 973
Cosmic explosions, 643
Cosmic Radiation Experiments, 448
Cosmic Ray and Solar Particle Investigation (COSPIN), 846
Cosmic Ray Effects and Activation Monitor (CREAM), 411, 414, 439, 440, 477, 517, 524, 532
Cosmic Ray Isotope Spectrometer (CRIS), 607, 807
Cosmic Ray Upset Experiment (CRUX), 380, 384
Cosmic Unresolved X-ray Background Instrument Using CCDs (CUBIC), 861
Cost Control Task Force, 214, 314, 569, 570
Covey, Richard O.
  STS-38, 361, 392
  STS-61, 367, 458
Creighton, John O.
  STS-36, 240, 361, 387
  STS-48, 363, 411
Crew and Equipment Translation Aids (CETA), 242, 356, 400
Crew return vehicle. *See also* Assured Crew Return Vehicle; Soyuz vehicle
  Assisted Crew Return Vehicle, 290
  budgets and funding for, 320
  European Crew Transport Vehicle, 310, 568
  requirement for in Space Station redesign, 294
  X-38 Crew Return Vehicle, 279, 310, 320–23, 568, 570
Crew Telesupport Experiment (CTE), 448
Crippen, Robert L., 24, 25, 26
Crisp, David, 970
Critical Ionization Velocity (CIV), 402
Crouch, Roger K.
  STS-83, 372, 521
  STS-94, 372, 525
Cryo Systems Experiment (CSE), 483
Cryogenic Flexible Diode Experiment (CRYOFD), 527
Cryogenic Heat Pipe Experiment (CRYOHP), 439
Cryogenic Infrared Radiance Instrumentation or Shuttle (CIRRIS), 402
Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere-Shuttle Pallet Satellite (CRISTA-SPAS), 162, 164, 261, 270–71, 368, 373, 479, 481, 528, 762
Cryogenic Thermal Storage Unit Flight Experiment (CRYOTSU), 547
Cryogenic Two Phase (CRYOTP), 465
Crystal Growth, experiment in, 406, 408, 421, 433, 434, 451–52, 531, 543, 544. *See also* Protein Crystal Growth (PCG) experiments
Crystal Vapor Transport Experiment (CVTE), 437
CSUN Aerospace Group, 406
Culbertson, Frank L., Jr
  STS-38, 361, 392
  STS-51, 366, 453
Cummings, Alan, 806
Curbeam, Robert L., Jr., 373, 528
Currie, Nancy J. Sherlock
  STS-57, 366, 449
  STS-70, 369, 489
  STS-88, 277, 317, 374, 549
Customer and Flight Integration office, Johnson Space Center, 194

D

Dactyl, 705, 707, 937
Daggett, California, 910, 911, 912, 914
Daimler Benz Aerospace, 310, 558
DARA. *See* Germany and German Space Agency (DARA)
Dartmouth College, 897
Data Interface Unit, 520
Davidsen, Arthur F., 981
Davis, N. Jan
  STS-47, 365, 429
  STS-60, 367, 460
  STS-85, 373, 528
Decade of Discovery in Astronomy and Astrophysics (AASC), 658–59
Deep Space 1, 141, 667, 668–69, 670, 773, 856–59
Deep Space 2, 739, 970
Deep space missions, 589
Deep Space Network (DSN)
  Advanced Satellite for Cosmology and Astrophysics (ASCA), 666
  antennae upgrade, 980
  Clementine, 723–24, 950
  Coronal-Sounding Experiment (SCE) and, 847
  Galileo, 701, 704
  location of stations, 666, 701
  Magellan, 697
  Mars Global Surveyor, 726
  Mars Pathfinder, 734
  Pioneer missions and, 746
  Solar and Heliospheric Observatory (SOHO), 682
  Wind, 677
Deep Space Probe Science Experiment (DSPSE), 720–21. *See also* Clementine
Deep Space Station, Weilheim, Germany, 617
Defense, Department of (DOD)
  Advanced Launch System (ALS), 77–78, 101
  Clementine, 156, 721, 722, 769
  DC-XA, 81
  ELVs and: acquisition through, 37; payloads launched for, 38–40, 46, 122, 146–47; Pegasus ELVs, 152; responsibility to improve, 22, 80; Scout ELVs, 59; Taurus ELVs, 154; Titan ELVs, 61, 155–57
  Far Ultraviolet Imaging Spectrograph (FUVIS), 761
  National Launch System, 78
  national space policy and, 22, 80
  payloads deployed for, 21, 61, 72, 159, 161, 239, 240, 242, 244, 360, 361, 365, 384, 393, 401–2

space science missions, 574
  Space Shuttle: experiments, 483; payload accommodations, 221; removal of DOD payloads, 61, 249, 439
  Space Test Program, 381, 761
  Space Transportation division, interface with, 29
Defense Advanced Research Projects Agency (DARPA), 55, 59, 80
Defense Meteorological Satellite Program (DMSP), 122, 123, 124
Defense Satellite Communication Systems (DSCS) III satellites, 45, 122, 123, 124, 168
Defense Support Program (DSP), 156, 168, 244, 363, 413
Delaboudinière, Jean Pierre, 877
Delta Clipper-Experimental Advanced (DC-XA), 76, 81, 170, 172, 173, 174
Delta Clipper-Experimental (DC-X), 80–81, 169, 170, 172, 173
Delta ELVs
  Delta 2000 series, 49
  Delta 3000 series, 49, 50, 54, 142
  Delta 4925, 50, 136
  Delta 5000 series, 50, 136
  Delta II, 20; acquisition of, 37; characteristics of, 52–53; Delta 6925, 50, 54, 143; Delta 7000 series, 51, 53, 54, 144, 668, 669; event sequence for geosynchronous mission, 51, 54, 145; launches with, 50–51, 136–41, 592, 605, 616, 673, 675, 737, 939, 960, 967, 969; management of, 29
  Delta III, 51, 141
  development of, 49–51
  launches with, 19, 21, 38–40, 49–51, 118, 136–41, 592, 594, 596, 657, 658, 767
  management of, 29
  success rate for launches, 38, 49, 118
  TSS experiments, 76–77, 138
DeLucas, Lawrence J., 364, 425
Denmark, 279
Dennis, Brian, 861
Descent Camera, 966
Descent Imager/Spectral Radiometer (DISR), 978
Descent Phase Instrument System, 966
Despun Platform Mechanism (DPM), 679
Destiny in Space, 255
Dexterous End Effector (DEF), 465
Dezhurov, Vladimir, 487
Differential Microwave Radiometer (DMR), 593, 595, 791, 792
Diffuse Infrared Background Experiment (DIRBE), 593–94, 595, 792
Diffuse Ultraviolet Experiment (DUVE), 137
Diffuse X-ray Spectrometer (DXS), 249, 440, 755–56, 774
Diffusion Coefficient Measurement Facility (DCMF), 506
Directional Discontinuities, 848
Discovery (OV-103)
  characteristics of, 217–18, 350
  flicker woodpecker damage, 489
  hinges, repair of, 401
  ionization glow documentation, 544
  launch vehicle function of, 20
  Mir support missions and, 220
  missions flown with, 159–64, 482
  Orbiter Maintenance Down Period (OMDP), 220, 249, 519
  Reaction Control System, 472
  STS-29, 159, 168, 238, 376–78
  STS-31, 159, 241, 388–89
  STS-33, 159, 168, 239, 384
  STS-39, 160, 243, 401–2, 762
  STS-41, 159, 168, 241–42, 390–91, 843
  STS-42, 160, 220, 244–46, 415–19
  STS-48, 160, 244, 411–12
  STS-51, 161, 252–54, 357, 449, 453–55, 763, 774, 775
  STS-53, 161, 249, 438–40
  STS-56, 161, 250, 441–43, 758, 774
  STS-60, 162, 255–56, 355, 460–63
  STS-63, 162, 261–62, 355, 357, 482–84, 774; Shuttle-*Mir* program, 300, 304, 555, 567; SPARTAN 204 mission, 761
  STS-64, 162, 260, 357, 471–75, 758, 774
  STS-70, 162, 168, 264, 489–90, 491
  STS-82, 163, 269, 358, 519–20, 630–33, 775
  STS-85, 164, 270–71, 528–30
  STS-91, 164, 275–76, 355, 541–44, 555
  STS-95, 164, 276, 355, 545–48, 633, 760–61, 775
Discovery Program
  budgets and funding for, 587, 714, 788
  Deep Space 2, 970
  development of, 577, 713–14
  ELVs for, 714
  missions: Comet Nucleus Tour (CONTOUR), 715, 938; Genesis, 715, 938; Lunar Prospector, 42, 119, 577, 715, 718–20, 772, 788, 938, 944–47; Mars Pathfinder, 139, 577, 715, 724, 731–35, 772, 788, 938, 960–63; Near Earth Asteroid Rendezvous (NEAR), 139, 577, 578, 679, 715–18, 770, 788, 938, 939–43; Stardust, 715, 938
  objectives of, 577, 713–15
  PI-led missions, 590, 714–15
Docking Compartment, 280
Docking Module, 266, 496, 497, 504
Doi, Takao, 359, 373, 533, 535
Doke, Tadayoshi, 864
Donnatello, 310
Doppler Gravity Experiment (DGE), 946, 947
Doppler Wind Experiment, 709, 934
Doppler Wind Experiment (DWE), 978
Dornier Systems, 660, 816, 825, 844
Doschek, George A., 880
Dowell Elementary School, Marietta, Georgia, 548
Dr. Ronald S. Nelson, Inc., 451
Droplet Combustion Apparatus, 526
Dryden Flight Research Center
  Aerospike engine, 176, 177
  Center of Excellence designation, 11
  F-15B Aerodynamic Flight Facility, 86, 179
  LASRE, 177, 178

mission area, 11
Pegasus ELV launches, 55
X-33, 86, 179
X-34, 82, 84
X-38 Crew Return Vehicle, 321–23
Duel Technique MAG, 975
Duffy, Brian
STS-45, 364, 420
STS-57, 366, 449
STS-72, 370, 498
Dugway Proving Ground, Utah, 86
Duke University, 407
Dunbar, Bonnie J.
STS-32, 361, 385
STS-50, 364, 425
STS-71, 369, 487
STS-89, 373
Duque, Pedro, 276, 374, 545
Durrance, Samuel T.
STS-35, 242, 362, 394
STS-67, 369, 485
Dust Detector Subsystem (DDS), 935
Dust Experiment (DUST), 847
DuVal High School, Lanham, Maryland, 547
Dynamic Explorer 1, 821

E

Earth
Cassini-Huygens and, 742
Center of Excellence for research, 584
images of taken from Shuttle, 243, 383
low-Earth orbit, 41
magnetic field, 749
measurement of distance between Shuttle and, 498
middle atmosphere, 260–61, 271, 480
Mission to Planet Earth program (Code Y), 214, 250, 260, 582
observation of, 278, 300, 305
ozone measurements, 246, 382, 473, 480, 534, 540
photographs of, 451
polar platform, 283
solar wind and, 265, 276
Spacelab mission research, 227
Terra Scout, 413
Earth Sciences and Applications Division (Office of Space Science and Applications), 581
Earth Sciences program, 214. *See also* Mission to Planet Earth program (Code Y)
EarthKAM, 537
Eastman-Kodak, 654
Economou, Thanasis, 962
Edith Brown Elementary School, 473
EDSYN, Inc, 408
Edwards, Joe Frank, Jr., 373, 536
Edwards Air Force Base
Haystack Butte (X-33 launch facility), 86, 175, 178, 180, 184, 185
launches from, 55
Space Shuttle launch and landing operations, 69, 217, 237, 502. *See also individual Space Shuttle missions*;
X-33 launch facility, 175, 177, 178, 180, 184, 185
EER Systems, 48, 49, 135
Effect of Cosmic Radiation on Floppy Disks and Plant Seeds Exposure to Microgravity, 408
Einstein, Albert, 652, 803, 848, 851
Einstein Observatory (HEAO-2), 652
El Paso (Texas) Community College, 534
Elachi, Charles, 975
Electric Fields and Ion Transport experiments, 620
Electric Fields Detector (EFD), 864
Electric Fields Instrument (EFI), 680, 872
Electrolysis Performance Improvement Concept Study (EPICS), 492
Electromagnetic Containerless Processing Facility (TEMPUS), 258, 259, 521, 526
Electron Analyzer and Magnetometer, 965
Electron Reflectometer (ER), 945–46, 947
Electronic Still Camera (ESC), 275, 517, 532
Element Integration Office, Marshall Space Flight Center, 204
Elrick Primary School, Aberdeen, Scotland, 507
Elsbernd, Robert L., 32
Emulsion Chamber Technology (ECT), 465
Endeavour (OV-105)
authorization to construct, 218
characteristics of, 217–19, 350
characteristics of and upgrades to, 219
construction milestones, 218, 350
extended duration orbiter, 219, 486
ISS assembly mission, 317, 318
missions flown with, 160–64; first, 64, 218
naming of, 218
Orbiter Maintenance Down Period (OMDP), 219, 221, 536
STS-47, 161, 248, 429–34
STS-49, 64, 160, 218, 246–47, 356, 422–24
STS-54, 161, 168, 249, 356, 440, 755, 756, 774
STS-57, 161, 228, 252, 253, 355, 356, 449–52, 474
STS-59, 162, 256–57, 260
STS-61, 161, 236, 255, 357, 458–59, 623, 628–30, 630, 774
STS-67, 162, 262–63, 485–86, 754, 775, 981
STS-68, 162, 260, 476–78
STS-69, 163, 265, 357, 491–93, 759, 775
STS-72, 163, 266, 358, 498–99
STS-77, 163, 267, 355, 505–7
STS-88, 64, 164, 277, 316–17, 319, 359, 549–51; ISS assembly mission, 277, 313, 315–17, 318, 319, 359, 374, 562–63
STS-89, 164, 274, 355, 536–37, 555
umbilical assembly from, 394
Energetic and Relativistic Nuclei and Electron (ERNE) experiment, 877
Energetic Gamma Ray Experiment Telescope (EGRET), 645, 646, 648, 834, 835, 836
Energetic Particle Acceleration, Composition and Transport (EPACT), 867, 868
Energetic Particle and Ion Composition (EPIC) Investigation, 863

Energetic Particle Composition and Neutral Gas Experiment (EPAC), 845
Energetic Particle Experiment, 686
Energetic Particle Instrument (EPI), 708, 933, 934
Energetic Particles Detector (EPD), 935
Energy, Department of, 146, 660, 741–42
Energy-mass Ion Spectrograph and Neutral-particle Imager, 965
Engineering and Science Tape Recorder, 520, 632
Engineering and Technical Base funding, 97
E-Nose, 547
Entech, 857
Enterprise, 20
Enterprise Development office (Office of Space Flight), 31, 32, 193
Eros, 715–16, 943
Esposito, Larry L., 977
Eta Carinea, 634, 637
Europa, 706, 710, 711, 712–13, 930, 931, 936
Europe
  Central Europe, imaging of, 256
  communication satellite, 46, 122, 125, 141
  IUE observers, 688
  LIDAR LITE experiment, 471
European Science Foundation, Space Science Committee, 740
European Space Agency (ESA). *See also* Compton Gamma Ray Observatory (CGRO)
  Altitude Sensor Package (ASP), 436
  APCF, 258
  astronauts on STS-74, 266
  BeppoSAX, 666, 855
  Biorack, 258, 259, 267
  Cassini-Huygens, 740–41, 743, 772
  Cluster spacecraft, 579, 672, 676
  Columbus Orbital Facility, 309
  Compton Telescope (COMPTEL), 646
  Crew Transport Vehicle, 310, 568
  ESA Council, 309, 568
  European Laser Docking System, 532
  European Retrievable Carrier (EURECA), 160, 161, 247–48, 252, 253, 356, 364, 366, 427, 428, 449
  Faint Object Camera (FOC), 621–22, 825
  GAS experiments, 462, 474, 493, 547
  Hermes spaceplane, 305
  Hubble Space Telescope, 626
  Hubble Space Telescope solar arrays, 624, 627, 628, 631
  Huygens science probe, 739, 743
  International Microgravity Laboratory (IML-2), 470
  International Solar Polar Mission (ISPM), 660
  International Solar-Terrestrial Physics (ISTP) program, 672
  International Space Station (ISS): agreements governing, 314–15, 569; contributions to, 279, 280, 305, 306, 313, 556, 568, 569; development of, 191, 277
  International Ultraviolet Explorer (IUE), 687–90
  IUE Newly Extracted Spectra (INES), 687
  Life and Microgravity Spacelab (LMS), 268, 509–11
  Liquid Gauging Technology Experiment, 451
  membership of, 279
  Microgravity Science Laboratory (MSL-1), 270
  Neurolab mission, 274
  Out of Ecliptic, 660
  printed and online information from, 189, 574
  Roentgen Satellite (ROSAT), 615
  Science Program Committee, 740
  Solar and Heliospheric Observatory (SOHO), 46–47, 125, 579, 609, 672, 675, 676, 680–83, 691, 770, 875–78
  Solid State Microaccelerometer Experiment, 406
  Space Science Department, 666
  Space Station *Freedom*: components, systems for, 285, 286; components for, 281, 284; development of, 190, 207, 280
  SPACEHAB payloads, 252
  Spacelab D-2, 445
  Spacelab design and development, 224
  Ulysses, 70, 71, 159, 241–42, 361, 660
European Space Research and Technology Centre, Noordwijk, Netherlands, 451
EVA Maneuvering Unit Television (EMU-TV), 765
Evaluation of Oxygen Integration with Materials/Thermal Management Processes (EOIM-III/TEMP 2A-3), 427
Evolved Expendable Launch Vehicle program, 22
Excel Interactive Science Museum, Salisbury, Maryland, 544
Expedite the Processing of Experiments to the Space Station Rack (EXPRESS), 526
Expendable launch vehicles (ELVs). *See also specific ELVs*
  acquisition of, 20, 37–38
  budgets and funding for, 33, 34, 35, 36, 89, 90, 93–94, 95, 115–17
  Centaur upper stage, 72
  Challenger explosion and, 21, 72
  characteristics of, 40–41
  commercial and private sector development and building of, 21–22, 23
  for Discovery Program, 714
  DOD's responsibility to improve, 22, 80
  failures and partial failures, 38, 39–40, 118
  families of, 19
  intermediate class, 94, 116
  international cooperative ELV mission requirements, 29, 97
  large class, 94, 117
  launches with, 19, 21, 38–40, 118, 575
  management of program for, 23, 26, 27, 29, 30, 32, 582
  medium class, 93, 116, 675
  payloads launched from, 38–41
  replacement of by Space Shuttle, 21
  small class, 55, 93, 115
  space science missions launched by, 573
  success rate for launches, 20, 21, 38–40, 118
  ultralite ELV launch services, 37, 592–93

Expendable Launch Vehicles Office, 30
Experiment Data System (EDS), 600, 802
Experiment Logistic Module, 279
Experiment of the Sun Complementing the ATLAS Payload and Education-II (ESCAPE-II), 480
Experimental Investigation of Spacecraft Glow (EISG), 465
Experimental vehicle procurement, 90
Explorer Concept Study Program, 605
Explorer Scouts, 433
Explorer spacecraft, 589
Explorers Program, 591–93
  Far Ultraviolet Spectroscopy Explorer (FUSE), X, 613–15, 781
  funding for, 781
  Medium-class Explorer missions (MIDEX), 592; IMAGE, 592, 809; MAP, 592
  missions, 790; ACE, 140, 579, 604–5, 606, 607, 772, 781, 806–9; COBE, 593–95, 596, 691, 767, 790, 791–92; EUVE, 137, 579, 691, 768, 790; RXTE, 139, 579, 599–600, 602, 650, 770, 781, 790, 801–3
  as model for Discovery Program, 714
  objectives of, 591
  Principal Investigator (PI)-led missions, 579, 590
  restructuring of program, 577, 579
  Small Explorer missions (SMEX), 591–92; budgets and funding for, 587; FAST, 147, 579, 591, 601–3, 691, 771, 790, 804–5; management of, 55, 152, 592; objectives of, 577; Pegasus for deployments, 55; SAMPEX, 152, 591, 598–99, 769, 790, 796–800, 809; success of, 577; SWAS, 148, 591, 610–12, 773, 790, 814–15; TRACE, 147, 579, 591, 608–10, 611, 691, 772, 790, 812–13; WIRE, 591–92
  Student Explorer Demonstration Initiative (STEDI) program, 592–93, 772; SNOE, 147, 592, 593, 605–6, 609, 772, 790, 810–11
Explorers Program Office, 605
Exploring the Unknown, Selected Documents in the History of the U.S. Civil Space Program, Volume V, xxii
Exposed Facility, 279, 284, 289, 556
Extended Duration Orbiter Medical Project, 414, 425
External Maintenance Solutions Team, 286, 564
External Maintenance Task Team (EMTT), 286, 564
External tank
  budgets and funding for, 92, 93, 108, 113
  characteristics of, 65–66, 165, 215, 216
  super lightweight external tank (SLWT), 276
Extravehicular activity (EVA)
  aboard *Mir*, 234, 302, 303
  categories of, 234
  EVA Development Flight Test (EDFT), 357–58, 498
  longest, 424
  Shuttle missions, 356–59; STS-37, 242, 356, 400; STS-49, 247, 356, 424; STS-51, 253, 357; STS-54, 249, 356; STS-57, 252, 356; STS-61, 236, 255, 357, 459, 628–29, 630, 774; STS-63, 261, 357, 484; STS-64, 357, 475; STS-69, 265, 357; STS-72, 358, 499; STS-76, 358, 504; STS-82, 358, 519–20, 630, 632, 775; STS-86, 272; STS-87, 359, 535; STS-88, 277, 316–17, 319, 359
  Spacelab tunnel adapter, 226
  spacesuit (extravehicular mobility unit [EMU]), 234, 235, 265, 499
  training for, 308
Extreme Ultraviolet (EUV) Spectrograph, 161, 269, 366, 763–64, 765, 988
Extreme Ultraviolet Explorer (EUVE), 137, 579, 595–97, 691, 768, 790, 793–95
Extreme Ultraviolet Imagine Telescope (EIT), 877
Extreme Ultraviolet Spectrometer (EUVS), 934, 935

F

Faint Object Camera (FOC), 621–22, 625, 825, 829
Faint Object Spectrometer (FOS), 358, 519, 625, 630, 632, 826, 827
Fairbanks, Alaska, 915, 921, 924
Fairchild Space, 793
Fairchild-Weston, 552
Fanale, Fraser P., 936
Far Infrared Absolute Spectrophotometer (FIRAS), 593–94, 595, 791–92
Far Ultraviolet (FUV) Spectrograph, 161, 269, 366, 763–64, 765, 766, 988
Far Ultraviolet Imaging Spectrograph (FUVIS), 482, 761
Far Ultraviolet Spectroscopy Explorer (FUSE), 592, 613–15, 781
Fast Auroral Snapshot Explorer (FAST)
  deployment of, 147, 579, 591, 601–3, 771, 790, 804–5
  ISTP program, 601
  objective of, 591, 771
  sounding rocket program and, 691
Fast Omnidirectional Non-scanning Energy-mass Analyzer, 965
"Faster, better, cheaper" concept, 577, 582, 587–88, 714, 718, 737, 772
Faster, Cheaper, Better (McCurdy), xxii
Fastrac engine, 176
Favier, Jean-Jacques, 371, 508
Federal Aviation Administration (FAA), 23
Federal Communications Commission (FCC), 41
Feldman, William, 806, 944
Ferguson, Earl, 211
Fettman, Martin J., 366, 455
Fichtel, Carle E., 835
Finland, 672
Finnish Meteorological Institute, 970
Fishman, Gerald J., 834
Fisk, Lennard A., 581, 582, 622
Fletcher, James, 282, 564
Flexible Beam Experiment (FLEXBEAM), 499
Flight Crew Operations Directorate, 233

Flight Demonstration Program (Office of Space Systems Development), 76
Flight Integration division (Office of Space Access and Technology), 29
Flight operations upgrades, 92, 106
Flight Systems (Office of Space Flight division), 24–25, 26, 193
Flight Systems Office (Office of Life and Microgravity Sciences and Applications), 211, 212
Flight telerobotic servicer (FTS), 285, 288
Floppy disks, 408
Flower and Vegetable Seeds Exposure to Space, 407
Fluid Acquisition and Resupply Experiment (FARE), 439, 450
Fluids Experiment Apparatus (FEA), 239, 379, 385
Fluxgate Magnetometer (FGM), 844
Foale, C. Michael
  aboard *Mir*, 270, 272, 303, 523, 531, 555
  STS-45, 364, 420
  STS-56, 365, 441
  STS-63, 261, 357, 368, 482, 484
  STS-84, 270, 372, 523
  STS-86, 272, 373, 531
Foamed Ultralight Metals, 407
Ford Aerospace, 552
Fort Churchill, Canada, 882–83
Fort Couch Middle School, Upper Saint Clair, Pennsylvania, 548
Fort Sumner, New Mexico, 693, 906–25
Four Rivers District, Boy Scouts, Gambrills, Maryland, 544
Fran, Hurricane, 512, 514
France and French Space Agency (Centre National d'Etudes Spatiales [CNES])
  ATLAS-1 instruments, 246
  balloon flights, 920
  ESA membership, 279
  Far Ultraviolet Spectroscopy Explorer (FUSE), 613, 615
  International Microgravity Laboratory (IML-2), 470
  International Solar-Terrestrial Physics (ISTP) program, 672
  Life and Microgravity Spacelab (LMS), 268, 509–11
  Mars Relay Radio System, 958
  Neurolab mission, 274
  Piroda module, 300
  Solar Spectrum (SOLSPEC), 480
  Spacelab D-2, 445
Frank, Louis A., 863, 874, 935
Franscati, Italy, 861
Freeman, Del, 180
French Gamma Telescope (FREGATE), 861
Frimout, Dirk D., 364, 420
Fritz, Theodore A., 873
Fröhlich, Claus, 878
Frontiers of Science Foundation, 407
Fujitsu Ltd., 408
Fulchignoni, Marcello, 978
Functional cargo block (FGB), 305, 306, 308, 311–12, 313, 314, 315, 556, 557, 567, 568, 569

G

G1 globular cluster, 635, 639
Gabriel, Alan, 877
Gabris, Edward, 29, 212
Gaffney, F. Drew, 362, 403
Galaxies
  ASCA discoveries, 852
  Astro-1, 752–53
  Astro-2, 754–55, 984–86
  collision of, 638, 641
  distances to, 641, 642
  galactic gases, x-ray radiation from, 249
  M100 Spiral Galaxy, 623, 624
  Milky Way, 613–14, 648, 650, 752, 754, 817, 836
  NGC 4151, 984
  NGC 4603 spiral galaxy, 641, 642
  PKS2155-304, 765
  quasars and, 640, 648, 836
Galaxy and the Universe theme, 583
Galilei, Galileo, 700–701
Galileo
  characteristics, instruments, and experiments, 700–702, 706, 932–37, 973; Atmosphere Structure Instrument (ASI), 708–9, 933; Doppler Wind Experiment, 709, 934; Dust Detector Subsystem (DDS), 935; Energetic Particle Instrument (EPI), 708, 933, 934; Energetic Particles Detector (EPD), 935; Extreme Ultraviolet Spectrometer (EUVS), 934, 935; Heavy Ion Counter (HIC), 935; Helium Abundance Detector (HD), 709, 710, 933; Lightning and Radio Emission Detector (LRD), 709, 933; Magnetometer (MAG), 935; Near-infrared Mapping Spectrometer (NIMS), 934; Nephelometer (NEP), 709, 933; Net Flux Radiometer (NFR), 709, 933; Neutral Mass Spectrometer (NMS), 709–10, 933; Photopolarimeter Radiometer (PPR), 934; Plasma Investigation Subsystem (PLS), 935; Plasma Wave Subsystem (PWS), 935; Radioisotope Thermoelectric Generators (RTGs), 741; Solid-state Imaging (SSI) camera, 934; Ultraviolet Spectrometer (UVS), 934
  deployment of, 159, 239, 360, 382, 383, 702–3, 767, 930, 932; delay of, 575, 577, 702
  discoveries and scientific contributions from, 708–13, 936–37
  firsts accomplished during mission of, 937
  funding for, 785
  IUS launch, 168
  mission events, 702–8, 710–11, 712–13, 930–31
  objective of, 578, 767, 932
  trajectory and orbits of, 703–4, 706, 710–11
Galley Iodine Removal Assembly (GIRA), 550
Gambia, 237
Gamma Ray Burst Spectrometer (GRaBS), 861
Gamma Ray Observatory (GRO). *See* Compton

Gamma Ray Observatory (CGRO)
Gamma Ray Spectrometer (KONUS), 677, 869
Gamma-ray Astrophysics Mission (GAMCIT), 506
Gamma-ray bursts, 643, 646, 647–50, 662, 671–72, 837, 847
Gamma-ray Spectrometer (GRS), 941, 945, 946, 953, 965
Ganymede, 710, 711, 712, 930, 931
Gardner, Guy S., 362, 394
Garmire, Gordon, 839, 861
Garneau, Marc, 370, 505
Garrett AiResearch, 552
Gas Imaging Spectrometers (GISs), 665, 849, 850
Gaspra, 705, 930, 937
Geiss, Johannes, 806, 845
Gelation of SOLS Applied Microgravity Research (GOSAMR), 417
Gemar, Charles D.
  STS-38, 361, 392
  STS-48, 363, 411
  STS-62, 367, 464
General Accounting Office (GAO), 7, 190, 307, 313, 574
General Dynamics
  Advanced Launch System (ALS), 78
  animal enclosure modules, 231
  Atlas ELVs, 43, 45, 72, 127, 128, 129, 131
  Centaur upper stage, 70
  Convair Division, 43
  ELV launch services, 37
  Space Station contract, 552
General Electric Company
  Astro-Space Division: Mars Observer, 952; Space Station development, 200, 281, 288, 552, 564
  RCA, 552
General Machine Building, Soviet Union, 291, 565
Generic Bioprocessing Apparatus (GBA), 440, 473
Genesis, 715, 938
Geographos, 721, 722–23, 948, 951
Geological Survey, U.S., 857
Geospace Corporation, 890
Geosynchronous orbit
  Atlas ELVs, 44, 130
  definition, 69
  Delta ELVs, 51, 54, 145
  Shuttle-IUS, 74
  Titan IV-IUS, 72
Geotail satellite, 50, 137, 579, 672, 673, 674–76, 769, 809, 862–65
German Aerospace Center, 537
German Aerospace Research Establishment (DLR), 445
Germany and German Space Agency (DARA). *See also* Compton Gamma Ray Observatory (CGRO); Orbiting and Retrievable Far and Extreme Ultraviolet Spectograph-Shuttle Pallet Satellite (ORFEUS-SPAS)
  ASTRO-SPAS, 253, 269, 762–63
  ATLAS-1 instruments, 246
  BREMEN Satellite (BREMSAT), 463
  Comet Rendezvous Asteroid Flyby (CRAF), 739
  Commercial Float Zone Facility, 267
  communication satellite, 124, 138
  Compton Telescope (COMPTEL), 646
  CRISTA-SPAS, 162, 164, 261, 270–71, 368, 373, 479, 481, 528, 762
  Deep Space Station, Weilheim, 617
  Electromagnetic Containerless Processing Facility (TEMPUS), 258, 259
  Energetic Gamma Ray Experiment Telescope (EGRET), 646
  ESA membership, 279
  Galileo, 701
  GAS experiments, 418, 506
  German Space Operations Center, Oberpfaffenhofen, 617
  International Microgravity Laboratory (IML-2), 470
  International Solar-Terrestrial Physics (ISTP) program, 672
  Microgravity Science Laboratory (MSL-1), 270
  Neurolab mission, 274
  Piroda module, 300
  Roentgen Satellite (ROSAT), 136, 579, 593, 615–18, 767, 816–18
  Slow Rotating Centrifuge Microscope (NIZEMI), 258
  Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX), 152, 579, 598–99, 769, 790, 796–800, 809
  space science satellite, 39
  Spacelab D-1, 445, 448
  Spacelab D-2, 161, 251, 354, 366, 445–48
  Spacelab funding, 212
  Student Experiment on ASTRO-SPAS (SEAS), 766
  X-band Synthetic Aperture Radar (X-SAR), 256, 257, 477
Gernhardt, Michael L.
  dogtag, 265
  STS-69, 265, 357, 369, 491
  STS-83, 372, 521
  STS-94, 372, 525
Gerrard, Thomas, 806
Get Away Special (GAS) program
  accommodations for on Shuttle, 222–23, 351
  budgets and funding for, 212
  containers for, 222
  management of, 194, 222
  number of payloads flown, 222
  rules for participating in, 222–23
  Shuttle missions: 100th payload, 255; STS-4, 222; STS-28, 381; STS-33, 384; STS-40, 406–8; STS-42, 418–19; STS-45, 421; STS-47, 433–34; STS-53, 249; STS-57, 451–52, 474; STS-59, 257, 468; STS-60, 255, 462–63; STS-64, 473–75; STS-67, 486; STS-68, 260, 477–78; STS-69, 493; STS-72, 499; STS-76, 503; STS-77, 506–7; STS-85, 529; STS-87, 534; STS-88, 551; STS-89, 537;

  STS-90, 540; STS-91, 543; STS-95, 547
Giacconi, Richardo, 652
Giacobini-Zinner comet, 575, 591
Gibson, Robert L.
  STS-47, 365, 429
  STS-71, 369, 487
Gierasch, Peter, 936
Girl Scouts, 544
Glass Fining, 537
Glassmeier, Karl-Heinz, 856
Glenbrook North High School, Northbrook, Illinois, 515, 548
Glenn, John H., Jr, 164, 276, 374, 545, 633
Global Geospace Science (GGS) initiative, 139, 579, 673–74, 675, 676, 679, 769, 770, 779
Global Oscillations at Low Frequencies (GOLF), 877
Global Positioning System (GPS)
  navigation with, 219, 322
  satellites for, launch of, 50, 51, 136–40
  Single String Global Positioning System, 550
  Space Integrated Global Positioning System,/Inertial Navigation System (SIGI), 551
Gloeckler, George, 806, 868
Glow Experiment (GLO), 439, 483, 492, 496
Goddard High Resolution Spectrograph (GHRS), 358, 459, 519, 625, 629, 630, 632, 826, 827
Goddard Space Flight Center
  balloon flights, 906, 907, 908, 912, 913, 914, 915, 916, 917, 918, 919, 921, 922, 924
  Center of Excellence designation, 11, 584
  Communication and Data Support, 196
  experiments sponsored by: BBXRT, 753, 983; CIRS, 973; CRRES, 820; DXS, 440, 756; EPACT, 867; GAS experiments, 408, 462, 475, 534; GCMS, 979; GRaBS, 861; HXRS, 671, 861; KONUS, 869; MAG, 940, 945–46; MAG/ER, 953, 956; MFI, 868; MOLA, 952, 955; NLR, 942; NMS, 709–10, 933; OEX program, 405; PSI, 873; ROMPS, 472; sounding rocket program, 882, 883, 884, 885, 886, 887, 888, 890, 893, 895, 896, 897, 898, 901, 902, 904, 905; SOXS, 861; SWE, 867; TGRS, 869; TIDE/PSI, 873; UIT, 752, 982; URAP, 845; XGRS, 940, 941
  GAS ballast payload, 452
  Hitchhiker Control Center, 223
  Laboratory for High Energy Astrophysics, 753
  management of, 32, 580
  mission area, 11
  programs developed or managed by: ACE, 605, 806; ASCA, 849; CGRO, 646, 833; Clementine, 948; COBE, 593, 791–92; EGRET, 646, 835; EUVE, 596, 793; Explorers Program, 616; FAST, 601, 602, 804; GAS program, 194, 222; Geotail satellite, 862; HETE/SAC-B, 671, 860; Hitchhiker program, 223; Hubble Space Telescope, 621, 626, 629, 631, 823, 829–30; ISTP, 672; IUE, 688; launch systems, 29; NEAR, 939; Polar, 871; ROSAT, 816; RXTE, 599–600, 801, 802; SAMPEX, 598, 796, 797, 798; Scout ELVs, 59; Small Explorer Data System, 598; Small Explorer program, 55, 152, 592; small payload carrier systems, 194; SNOE, 810; SOHO, 875; space science missions, 584; Spacelab, 196; SPARTAN 201-01, 758; STIS, 829–30; SWAS, 814; TDRS system, 194; TRACE, 812; Wind, 866
  Space Station Work Package 3, 198, 200–201, 281, 288, 552
  Space Telescope Operations Control Center, 459, 631
  STS-35, success of, 398
Godwin, Linda M.
  STS-37, 362, 399
  STS-59, 367, 467
  STS-76, 358, 370, 502, 504
Gold, Robert, 806
Goldin, Daniel S.
  "Access to Space" study, 80
  "faster, better, cheaper" concept, 577, 582, 587–88, 714, 772
  Living With a Star initiative, 580
  METEOR project, 48–49
  as NASA administrator, 27, 28, 80, 181, 206, 210, 211, 291, 565, 577, 582, 584
  Program Committment Agreement, 674
  RLV program, 182
  safety of *Mir*, 304, 531
  SIRTF program, 659
  Space Station program, 208, 293, 296, 297, 298, 311, 314, 315, 566, 568, 569
Goldstone, California, 666
Golubkina crater, 699, 701
Gorbachev, Mikhail, 291, 565
Gordon, Tropical Storm, 260, 479
Gore, Albert A.
  Space Station program, 297, 298, 565, 566, 567
  X-33, 85–86, 173
Gore-Chernomyrdin Commission, 298, 567
Goree, Jesse F., Jr., 204
Grabe, Ronald J.
  STS-30, 360, 379
  STS-42, 363, 415
  STS-57, 366, 449
Grand Coulee, Washington, Elementary School, 544
Graphic Retrieval and Information Display (GRID) computer, 386
Gravitational Wave Experiment (GWE), 848
Gravity Probe-B, 784
GRB 970228 gamma-ray burst, 643
GRB 971214 gamma-ray burst, 650
Great Britain. *See* United Kingdom/Great Britain
Great Observatories, 652. *See also* Advanced X-ray Astronomical Facility (AXAF); Compton Gamma Ray Observatory (CGRO); Hubble Space Telescope
  deployment of, 3, 159, 241, 242, 578, 620
  objectives of, 589, 620
  SIRTF, 658
Greece, 672
Gregory, Frederick D.
  STS-33, 360, 384

STS-44, 363, 413
Gregory, William G., 369, 485
GRO J1655-40 (X-ray Nova Scorpii), 649
Growth and Morphology, Boiling and Critical Fluctuations in Phase Separating Supercritical Fluids (GMSF), 542
Growth Hormone Concentration and Distribution (GHCD) in Plants, 383
Grumman Aerospace, 646
Grumman Space and Electronics Group, 208, 296, 552
Grün, Eberhard, 847, 935, 973
Grunsfeld, John M.
  STS-67, 369, 485
  STS-81, 371, 517
GTE Laboratories, Inc., 406, 421
Guided Precision Delivery System, U.S. Army, 321
Guidoni, Umberto, 370, 500
Gunn, Charles R., 24, 25, 27, 29, 30
Gurnett, Donald A., 872, 935, 976
Gutierrez, Sidney M.
  STS-40, 362, 403
  STS-59, 367, 467

H

Habitation module, U.S., 284, 285, 286, 288, 309, 556, 557
Hadfield, Chris A., 370, 496
Haerendal, Gerhard, 820, 821
Hale-Bopp comet, 529, 662, 680
Halley's Comet, 750, 751, 824
Halsell, James D., Jr.
  STS-65, 367, 469
  STS-74, 370, 496
  STS-83, 372, 521
  STS-94, 372, 525
Hamilton, D., 797
Hamilton Standard, 552
Hammond, L. Blaine, Jr.
  STS-39, 362, 401
  STS-64, 368, 471
Hampton Elementary School, Lutherville, Maryland, 515
Handheld, Earth-oriented, Real-time, Cooperative, User-friendly, Location-targeting and Environmental System (HERCULES), 439, 490
Hansen, Lauri, 210
Harbaugh, Gregory J.
  STS-39, 362, 401
  STS-54, 249, 356, 365, 440
  STS-71, 369, 487
  STS-82, 358, 372, 519, 520, 632
Hard X-ray Spectrometer (HXRS), 671, 860, 861
Hard X-ray Telescope (HXT), 683–84, 880
Harms, R. F., 826
Harri, Ari-Matti, 970
Harris, 552
Harris, Bernard A., Jr.
  STS-55, 366, 444
  STS-63, 261, 357, 368, 482, 484
Harris, David W., 32
Harrison, Richard, 875
Hartsfield, Henry, 203
Harvard University
  balloon flights, 906, 910, 911, 912, 915, 921
  Galileo, 936
Harvard-Smithsonian Center for Astrophysics, 814, 839
Hasselblad camera, 470
Hauser, Michael, 792
Hawaii, 651, 716
Hawley, Steven A.
  STS-31, 361, 388
  STS-82, 372, 519, 632
Hawthorne, Krauss, and Associates, LLC, 183
Hawthorne Report, 183
Haystack Butte, Edwards Air Force Base (X-33 launch facility), 86, 175, 178, 180, 184, 185
Haystack Radar, Tyngsboro, Massachusetts, 439
Hearts in Space, 529
Heat Pipe Performance Experiment (HPP), 437, 480
Heavy Ion Counter (HIC), 935
Heavy Ion Large Area Proportional Counter Telescope (HILT), 599, 797
Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies (HI-SCALE), 846
Helms, Susan J.
  STS-54, 365, 440
  STS-64, 368, 471
  STS-78, 371, 508
Hennen, Thomas J., 363, 413
Henricks, Terence T.
  STS-44, 363, 413
  STS-55, 366, 444
  STS-70, 369, 489
  STS-78, 371, 508
Herbig Haro 30, 634
Hercules Aerospace Company, 51, 61, 149
Hermes spaceplane, 305
Hernandez, Ana Maria, 860
Hieb, Richard J.
  STS-39, 362, 401
  STS-49, 356, 364, 422, 424
  STS-65, 367, 469
High Energy Accelerator Research Organization (KEK), 922
High Energy Astronomy Observatory (HEAO), 575
  HEAO-1, 652
  HEAO-2 (Einstein Observatory), 652
High Energy Astrophysics Branch, 584
High Energy Astrophysics Science Archive Research Center, NASA, 666
High Energy Timing Experiment (HEXTE), 600, 602, 801, 802
High Energy Transient Experiment (HETE), 147, 148, 576, 671–72, 771, 860–61
High Energy Transmission Grating (HETG) spectrometer, 657, 839–40, 841
High Mass Resolution Spectrometer (MASS), 868
High Pressure Gas Scintillator Proportional Counter, 855

High Resolution Accelerometer Package (HiRAP), 397, 405
High Resolution Camera (HRC), 656, 657, 839, 840
High Resolution Mapping Spectrophotometer, 964
High Resolution Mirror Assembly, 654, 656–57
High Resolution SHuttle Glow Spectroscopy (HRSGS), 454
High Speed Photometer (HSP), 459, 625, 627–28, 828, 829
High-energy Particles (HEP) Investigation, 864
High-resolution Camera, 950
High-resolution imagers (HRIs), 615, 616, 617, 817
Hilmers, David C.
  STS-36, 361, 387
  STS-42, 363, 415
Hirayama, Tadashi, 880
Hire, Kathryn P., 374, 538, 540
Historical Reference Collection, xxi
Hitchhiker Ejection System, 550
Hitchhiker program
  accommodations for on Shuttle, 223, 351
  Advanced Carrier Customer Equipment Support System, 223
  budgets and funding for, 212
  Diffuse X-ray Spectrometer (DXS), 249, 756
  HH-Jr., 223, 351
  management of, 223
  purpose of, 223
HL-20 crew return vehicle, 320
Hoffman, Jeffrey A.
  STS-35, 242, 362, 394
  STS-46, 364, 427
  STS-61, 357, 367, 458, 459, 628, 629
  STS-75, 370, 500
Hoffman, Robert, 820
Hofstadter, R., 835
Hollomon Air Force Base, 82
Holloway, Harry, 211
Holographic Optics Laboratory (HOLOP), 446
Honeywell Corporation, 62, 552, 679
Hood, Lon, 945
Hook, W. Ray, 283, 564
Hopkins, Joseph P., Jr., xxii
Hopkins, Joshua B., xxii
Hopkins Ultraviolet Telescope (HUT)
  Astro-1, 396, 750–51, 752, 981
  Astro-2, 485, 754–55, 981, 984–86
Hord, Charles, 934, 935
Horizon 2000 space science program, 741
Horowitz, Scott J.
  STS-75, 370, 500
  STS-82, 372, 519, 632
Hot Plasma Analyzer (HYDRA), 680, 872
Housing and Urban Development, Department of, 37
Houston, Texas, 296, 313. *See also* Johnson Space Center
Hovestadt, Dieter, 797, 806, 877
Howard, H. Taylor, 936
Hubbard, G. Scott, 945
Hubble, Edwin, 621, 641
Hubble Orbiting Systems Test (HOST) platform, 164, 276, 374, 546, 633, 775
Hubble Space Telescope
  characteristics, instruments, and experiments, 623–26, 627, 633, 823–32; Corrective Optics Space Telescope Axial Replacement (COSTAR) system, 357, 459, 627–28, 829; Data Interface Unit, 520; Engineering and Science Tape Recorder, 520, 631, 632; Faint Object Camera (FOC), 621–22, 825, 829; Faint Object Spectrometer (FOS), 358, 519, 630, 632, 826, 827; fine guidance sensors, 358, 520, 624–25, 630, 631, 632, 828–29; Goddard High Resolution Spectrograph (GHRS), 358, 459, 519, 629, 630, 632, 826, 827; High Speed Photometer (HSP), 459, 627–28, 828, 829; Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 358, 519, 630, 632, 831–32; Optical Control Electronics Enhancement Kit, 520; solar arrays, 459, 520, 623, 624, 627, 628, 629, 632; solid-state recorder, 520, 631, 632; Space Telescope Imaging Spectrograph (STIS), 358, 519, 630, 632, 829–30; Wide Field and Planetary Camera 2 (WFPC2), 459, 627–28, 829; Wide Field and Planetary Camera (WFPC), 357, 459, 621, 623, 628, 824
  communication to ground through TDRS, 631
  defects of, 578, 621–23
  deployment of, 159, 241, 361, 388, 578, 620, 621, 767, 823; delay of, 575
  development and management of, 620–21, 626, 629, 823
  discoveries and scientific contributions from, 634–44, 650, 709, 832
  funding for, 778
  HOST mission, 164, 276, 374, 546, 633, 775
  images taken by, 621–22, 624
  International Ultraviolet Explorer (IUE) compared to, 689
  Jupiter, 755, 986
  naming of, 621
  objective of, 589, 620, 633–34, 767, 823
  Optical Telescope Assembly, investigation of, 622–23
  orbit of, 624, 632, 823, 841
  servicing missions: SM1 (STS-61), 161, 234, 236, 255, 357, 367, 458–59, 578, 623, 626–30, 774, 823, 829; SM1, preparation for, 253, 357; SM2 (STS-82), 163, 269, 358, 372, 519–20, 630–33, 775, 823, 829–32
  as Shuttle payload, 221
  Web site for, xxiii, 634
Hubble Space Telescope Optical Systems Board of Investigation, 622–23
Hughes Aircraft Company, 701, 927, 932
Hughes Danbury Optical Systems, 654
Hughes Electron Dynamics Division, Spectrum Astro, Inc., 856
Hughes-Fulford, Millie, 362, 403
Human Exploration and Development of Space (HEDS) Enterprise, 30, 210
Human Factors Configuration, 550

Human immune function, 550
Human Space Flight (HSF) appropriations
  launch systems, 33–34, 35, 36
  Programmed Budget, 92–95
  programs funded with, 6, 12, 13, 89, 90
  Space Station program, 213, 215, 324–26
  Spacelab, 212
Human spaceflight programs. *See also specific programs*
  availability of information about, 189–90
  budgets and funding for, 189–90, 212–15, 324–48
  last decade review, 190
  management of, 192–212
  overview of, 190–92
Human Spaceflight Web page, xxiii
Hunten, Donald M., 936
Huntress, Wesley, 581, 582, 584, 585, 714
Huntsville, Alabama, 228, 258, 270
Hurley, Kevin, 847
Huygens, Christiaan, 740
Huygens Atmospheric Structure Instrument, 978
Huygens science probe, 739, 741, 743. *See also* Cassini-Huygens
  Aerosol Collector and Pyrolyser (ACP), 979
  Descent Imager/Spectral Radiometer (DISR), 978
  Descent Module, 743
  Doppler Wind Experiment (DWE), 978
  Entry Assembly, 743
  Gas Chromatograph Mass Spectrometer (GCMS), 979
  Huygens Atmospheric Structure Instrument, 978
  Permittivity and Electromagnetic Wave Analyzer, 978
  probe support equipment, 743
  Surface-science Package (SSP), 979

I

IBM, 552
Ida, 705, 707, 930, 937
Idaho Falls, Idaho, 174
IKI, 970
ILC, 552
Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), 592, 809
Imaging Particle Spectrometer for Energetic Neutral Atoms (ISENA), 861
Imaging Science Subsystem (ISS), 974
IMAX Corporation Camera experiments
  IMAX Cargo Bay Camera (ICBC), 253, 255, 388, 428, 496, 551
  IMAX Handheld Camera, 253, 255, 388, 454, 483
  Mir images, 513
  Remote IMAX Camera System (RICS), 454, 764–65
  Shuttle missions: STS-29, 378; STS-31, 388; STS-32, 386; STS-34, 383; STS-46, 428; STS-51, 253, 454, 764–65; STS-61, 255; STS-63, 483; STS-71, 488; STS-74, 496; STS-79, 513; STS-88, 551
Imperial College of Science & Technology, 844, 975
Independent Agencies appropriations bills, 37
Independent Television News of England, 434
India
  IUE observers, 688
  missile technology to, 297, 566
  payloads launched for, 21
  satellites, 136
Indonesia, 125, 136, 137, 471
Inertial upper stage (IUS)
  characteristics, 72, 167
  deployments with, 69, 74, 168
  TDRS deployment, 168, 238
  Ulysses deployment, 71, 168, 241, 390
In-flight maintenance, 236
Information Systems, 784
Infrared Astronomy Satellite (IRAS), 658
Infrared Background Signature Survey experiment, 160
Infrared Interferometer Spectrometer (IRIS), 974
Ingersoll, Andrew P., 936
In-Space Commercial Processing experiments, 406
Inspector General, Office of, 6, 87, 185, 304
Institut d'Aeronomie Spatiate de Belgique, Belgium, 848
Institute for Interplanetary Space Physics (Instituto di Fisica dello Spazio Interplanetario), 861
Institute of Chemistry and Physics (RIKEN), 861
Institute of Physical Sciences and Technology, 868
Institute of Space and Astronautical Science of Japan (ISAS), 137, 664, 665–66, 675, 684, 862, 864, 881
Institutions (Office of Space Flight division), 24–25, 193
Instituto de Astronomia, Italy, 848
Instituto de Tecnologie e Studio Delle Radiaziioni Extrterrestri (TESRE), 919
Instituto di Fisica dello Spazio Interplanetario (Institute for Interplanetary Space Physics), 861
Instituto Nacional de Pesquisas Espaciais (INPE), 280
INTELSAT Solar Array Coupon, 242, 390
INTELSAT VI satellite, 246–47, 356, 364, 422, 424
Interim Control Module, 312, 568
Interim Operational Containimation Monitor (IOCM), 380, 385, 413
International Cometary Explorer (ICE), 575
International Extreme Ultraviolet Hitchhiker (IEH), 271, 276, 492, 529, 547
International Maritime Satellite Organization, 137
International Microgravity Laboratory (IML)
  IML-1, 160, 244–45, 354, 363, 415–17
  IML-2, 162, 254, 258–59, 354, 367, 470
International Reference Guide to Space Launch Systems (Isakowitz, Hopkins, and Hopkins), xxii
International Solar Polar Mission (ISPM), 660
International Solar-Terrestrial Physics (ISTP) program

  characteristics of program, 672
  Collaborative Solar-Terrestrial Research (COSTR) program, 672, 673
  Global Geospace Science (GGS) initiative, 139, 579, 673–74, 675, 676, 679, 769, 770, 779
  management of, 672
  objectives of, 672–73
  participants in, 672
  programs included in, 139, 579, 601, 608, 672, 675, 676, 680, 769, 770, 771
International Space Station (ISS)
  agreements governing, 297–98, 314–15, 316, 566, 567, 569
  assembly of: completed assembly, 321, 322; contract for, 307; on-orbit assembly, 315–17; orbital events summary, 317, 562–63; phases of, 192; preparations for, 274, 359, 499, 535; schedule for, 304, 305–7, 312–13, 557, 559, 560, 567, 569; Shuttle missions for, 277, 313, 315–17, 318, 319, 359, 374, 549, 562–63
  assembly techniques, practice of, 266, 484
  budgets and funding for, 191, 213, 305, 306, 307, 312, 313–14, 568, 570
  cancellation attempts by Congress, 306, 567, 568
  chronology of, 567–70
  commemorative plaque, 315, 316
  components, systems, and modules, 307, 321, 322; air purification system, 309; air purification system testing, 568; Androgynous Peripheral Attach System, 315; attached pressurized module, 557; Automated Transfer Vehicle, 279, 309–10, 568; Columbus Orbital Facility, 279, 280, 305, 310, 313, 556, 558, 568, 569; communication and tracking systems, 309; contributions by partners, 322; Docking Compartment, 280; docking modules, 556; Experiment Logistic Module, 279; Exposed Facility, 279, 556; functional cargo block (FGB), 305, 306, 308, 311–12, 313, 314, 315, 556, 557, 567, 568, 569; Interim Control Module, 312, 568; Japanese Experiment Module, 279, 306, 556, 557; laboratory accommodations, 317, 563; Mobile Servicing Systems, 279, 556; Multi-Purpose Logistic Modules, 280, 310; Orbiter Space Vision System (OSVS), 271; Passive Common Berthing Mechanism, 315; power platform, 306, 307, 556, 557; pressurized mating adapters, 315; Science Power Platform, 280; service module, 280, 305, 306, 313, 556, 568; solar array, 306, 307; Space Station Remote Manipulator System (SSRMS), 279; Space Vision System, 279; Special Purpose Dexterous Manipulator (SPDM), 279, 306, 316, 319; Technology Experiments Facility, 280; Unity module, 192, 277, 278, 315–17, 318–20, 374, 549, 561, 562–63, 570; Universal Docking Module, 280; U.S. habitation module, 309, 556, 557; U.S. laboratory module, 306, 308, 556, 557; Water Recovery System, 308, 568; Zarya module, 192, 277, 278, 280, 315, 316–17, 319–20, 549, 561, 562–63, 570
  construction of components, 308–9, 568
  contracts for activities related to, 64, 304, 307, 567, 568
  Cost Control Task Force, 214, 314, 569, 570
  crew, number aboard, 305
  development of, 191, 196, 277–78, 304; Shuttle-*Mir* program as support for, 64, 191–92, 278
  EVA Development Flight Test (EDFT), 357–58
  experiments conducted on, 268, 278
  lift capability, 307
  management of program for, 197, 208–10, 277–78
  orbit of, 278, 305
  orbiters capable of missions to, 220, 221
  partners and contributors to, 191, 192, 279–80, 297–98, 304, 309–12, 322, 556, 566–67, 568, 569
  payload capacity for, 276
  preparations for, 64, 356
  problems and delays with, 192
  Risk Mitigation Experiments, 272, 497, 542
  Russia as partner, 297–98, 306, 566–67; political and financial problems, 213, 305, 311–12, 314, 568
  size of, 278
  System Design Review, 305–6, 567
International Sun Earth Explorer (ISEE), 864
International Ultraviolet Explorer (IUE), 687–90
Interplanetary Monitoring Platform (IMP)-8, 686–87
Interstellar Medium Absorption Profile Spectrograph (IMAPS), 269, 764, 765, 766, 988
Interstellar Probe mission, 746
Intravehicular activity (IVA), 235
INVAP S. W., 860
Investigations into Polymer Membrane Processing (IPMP), 389, 390, 410, 412, 417, 421, 426, 454
Investigator Working Group, 234
Io, 706, 711–12, 713, 752, 755, 930, 931
Iodine and water system, 550
IOFFE Physical Technical Institute, 869
Ion and Neutral Mass Spectrometer (INMS), 974
Ion propulsion engine, 669, 670, 856
Ionospheric Irregularity Simulator experiments, 620
Ionospheric Modification experiments, 619–20
Ionospheric Plasma Spectrometers, 965
Ip, Wing-Huen, 936
Ireland, 672
Isakowitz, Steven J., xxii
Israel, Guy M., 979
Israeli Space Agency Investigation About Hornets (ISAIAH), 432
Istituto Technico Commerciale Riccatl, Treviso, Italy, 548
ITA, Inc., 442
Italian Research Interim Stage (IRIS), 249, 365, 435

Italy and Italian Space Agency (Agenzia Spaziale Italiana [ASI])
  BeppoSAX, 125, 578, 666, 771
  Cassini, 739
  Cassini-Huygens, 772
  ESA membership, 279
  International Solar-Terrestrial Physics (ISTP) program, 672
  International Space Station (ISS), 191, 280, 310, 556
  Italian-Dutch telescope, 40, 125
  Laser Geodynamic Satellite II, 161, 249
  Life and Microgravity Spacelab (LMS), 268, 509–11
  Tethered Satellite System (TSS), 74, 160, 247, 248, 364, 370, 427, 428, 500, 501
  X-band Synthetic Aperture Radar (X-SAR), 256, 257, 477
Itek Corporation, 652
IUE Newly Extracted Spectra (INES), 687
Ivins, Marsha S.
  STS-32, 361, 385
  STS-46, 364, 427
  STS-62, 367, 464
  STS-81, 371, 517

J

Jacobson, Ralph, 304
James Canadian Research Council, 882
Janis, Typhoon, 428
Japan
  Advanced Satellite for Cosmology and Astrophysics (ASCA), 579, 664–66, 769, 849–53
  Akebono satellites, 821
  ATLAS-1 instruments, 246
  communication satellite, 124, 125, 155
  female astronauts, 258
  Flower and Vegetable Seeds Exposure to Space, 407
  Geotail satellite, 50, 137, 579, 672, 673, 674–76, 769, 809
  High Energy Accelerator Research Organization (KEK), 922
  IMAX filming of, 388
  Institute of Space and Astronautical Science (ISAS), 137, 664, 665–66, 675, 684, 862, 864, 881
  International Microgravity Laboratory (IML-2), 470
  International Solar-Terrestrial Physics (ISTP) program, 672
  International Space Station (ISS): agreements governing, 298, 314–15, 569; contributions to, 306, 556; development of, 191, 277
  Manipulator Flight Demonstration (MFD), 271, 529
  Microgravity Science Laboratory (MSL-1), 270
  National Astronomical Observatory, 684, 880
  National Space Development Agency (NASDA), 270, 279, 280, 429–32, 470
  Neurolab mission, 274
  payloads launched for, 21
  SIR-C/X-SAR imaging, 477
  Space Flyer Unit, 266
  space flyer unit, 370
  Space Station *Freedom*: components for, 281, 284, 285, 287, 289; development of, 190, 207, 280
  Spacelab D-2, 445
  Spacelab funding, 212
  Spacelab-J, 161, 248, 354, 364, 429–32
  Yohkoh/Solar-A, 683–85, 768, 879–81
Japanese Experiment Module
  Freedom, 284, 285, 287
  ISS, 279, 306, 556, 557
Japanese Space Flyer Unit, 498
Java, 428
Jefferys, William H., 828
Jemison, Mae C., 365, 429
Jernigan, Tamara E.
  STS-40, 362, 403
  STS-52, 365, 435
  STS-67, 369, 485
  STS-80, 371, 514, 516
Jet Propulsion Laboratory (JPL)
  Advanced Composition Explorer (ACE), 806, 807
  Atmospheric Structure Instrument/Meteorology Package (ASI/MET), 961
  Autonomous Operations System, 857
  Autonomous Optical Navigation, 857
  balloon flights, 906, 907, 908, 909, 910, 911, 913, 914, 916, 917, 920, 921, 922, 924
  Beacon Monitor Operations, 857
  Cassini-Huygens, 971
  Celestial Mechanics, 936
  Center of Excellence designation, 11, 584
  Chandra (AXAF), 657
  Comet Rendezvous Asteroid Flyby (CRAF), 739
  Deep Space 1, 668, 856
  Doppler Gravity Experiment (DGE), 946
  Galileo, 701, 704, 932, 936
  GAS experiments, 478
  Heavy Ion Counter (HIC), 935
  Magellan, 697, 927
  management of, 580
  Mars Climate Orbiter, 967
  Mars Global Surveyor, 954
  Mars Observer, 952
  Mars Pathfinder, 960
  Mars Polar Lander, 969
  Mars Surveyor Project '98 Office, 735
  Meteorology instruments, 970
  mission area, 11
  Near-infrared Mapping Spectrometer (NIMS), 934
  overview of, 4
  Power Activation and Switching Module, 859
  Pressure Modulator Infrared Radiometer (PMIRR), 953, 968
  Radio Detection and Ranging (RADR) instrument, 975
  Radio Science Experiment, 942

  Radio Science Subsystem (RSS), 976
  Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX), 798
  Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET II), 857
  space science missions, management of, 584
  Spitzer Space Telescope (Space Infrared Telescope Facility [SIRFT]), 659
  Student Nitric Oxide Explorer (SNOE), 606
  Ulysses, 843
  Ulysses Comet Watch group, 662
  Wide Field and Planetary Camera (WFPC), 824; WFPC2, 628, 829
  X-band Synthetic Aperture Radar (X-SAR), 256
Jett, Brent W., Jr.
  STS-72, 370, 498
  STS-81, 371, 517
Johns Hopkins University
  Applied Physics Laboratory: Advanced Composition Explorer (ACE), 604, 605, 806; balloon flights, 916, 920; Energetic Particle and Ion Composition (EPIC) Investigation, 863; Energetic Particles Detector (EPD), 935; Near Earth Asteroid Rendezvous (NEAR), 715, 717, 939–40; NEAR Mission Operations System Ground Segment, 715; Science Data Center, 715
  Center for Physics and Astronomy, 613
  Far Ultraviolet Spectroscopy Explorer (FUSE), 613, 615
  Galileo, 936
  Hopkins Ultraviolet Telescope (HUT), 752, 981
  Magnetospheric Imaging (MIMI) Mass Spectrometer, 975
  sounding rocket program, 882, 885, 886, 891, 894, 899, 901, 902
  Space Telescope Science Institute (STScI), xxiii, 621, 626
Johnson Space Center
  astronaut training and selection, 232
  budgets and funding, 34
  Center of Excellence designation, 11
  CMAM procurement, 227
  crew return vehicles, 321
  Customer and Flight Integration office, 194
  Engineering director, 27
  GAS experiments, 506
  Hubble Space Telescope, 626, 629, 823
  International Space Station (ISS), 191
  L3 project camera, 386
  management of, 28, 31
  mission area, 11
  Mission Control Center, 267, 490
  OEX program, 405
  Space and Life Sciences Directorate, 483
  Space Shuttle program: management of, 193–94, 195, 490; orbiters, 65, 193–94; processing work, 64, 65, 193–94
  Space Shuttle Program Office, 196
  Space Station management, 197, 204, 296, 566; contractor-led joint vehicle integration team, 206, 208; crew and ground control training, 206; host Center for Space Station *Alpha*, 208; Work Package, 198, 199–200, 206, 207, 281, 552
  SPACEHAB experiments, 450, 460
  Spacelab management, 196
  X-38 Crew Return Vehicle, 321, 568
Jones, Thomas D.
  STS-59, 367, 467
  STS-68, 368, 476
  STS-80, 371, 514, 516
Jupiter
  Astro-1, 752, 986
  Astro-2, 755, 986
  Cassini-Huygens and, 742
  Galileo, 700–713, 930, 931, 936–37
  Hubble Space Telescope, 755, 986
  missions to explore, 575
  Pioneer 10, 745
  Shoemaker-Levy 9 comet and, 634, 635, 706, 707, 717
  Ulysses, 661, 662, 663, 842
  Voyager missions, 748, 980

K

Ka-Band Solid-State Power Amplifier, 668, 669, 858
Kadenyuk, Leonid K., 272, 373, 533, 534
Kagoshima Space Center, Japan, 685, 849, 879
Kavandi, Janet Lynn, 374, 541
Keating, Gerald M., 959
Keller, H. Uwe, 969
Kennedy Space Center
  Advanced X-ray Astronomical Facility (AXAF), 655, 838
  budgets and funding, 34
  Center of Excellence designation, 11
  Certification of Flight Readiness, 194
  Chandra (AXAF), 838
  Compton Gamma Ray Observatory (CGRO), 645, 833
  employee as astronaut candidate, 540
  Flight Readiness Review, 194, 388
  Hubble Space Telescope, 621, 626, 630, 823
  Human Spaceflight Web page, xxiii
  International Space Station (ISS), 309, 310–11, 313
  Launch Site Support Management, 196
  Lunar Prospector, 718, 944
  management of, 26, 28, 31
  Mars Global Surveyor, 954
  mission area, 11
  Mission Management Team, 194
  Olympic Torch Relay, 508
  Payload Operations Control Center, 253
  responsibilities of, 29, 194
  Space Shuttle launch and landing operations, 69, 194, 217; abort modes and, 237; first landing for *Atlantis*, 392; first scheduled landing, 244; Fran, Hurricane, 512, 514; Gordon, Tropical Storm, 260, 479; Mobile

    Launch Platform, 385; night landing, 454; Pad 39-A modifications, 250–51, 385. *See also individual Space Shuttle missions*;
  Space Shuttle program: management of, 194, 195; processing work, 64, 65
  Space Station management, 202
  Space Station Processing Facility, 202, 206
  Spacelab management, 196
  SPARTAN satellites, 758, 759
  Ulysses, 843
  Voyager missions, 980
  Yohkoh/Solar-A, 685
Keppler, Erhardt, 845
Key Largo, Florida, 532
Khrunichev, 305, 306, 308, 311–12, 313, 568
Kidsat, 503, 517, 532
Kinkaid School, 473
Kirtland Air Force Base, Phillips Laboratory, 80, 175, 859
Kiruna, Sweden, 882, 888
Kivelson, Margaret G., 935
Klaus, Tropical Storm, 395
Klecker, Berndt, 797, 806
Kliore, Arvydas, 976
Kodiak Launch Complex, Alaska, 41
Kohl, John, 876
Kohrs, Richard H., 25, 26, 28, 203, 204, 205, 206, 208
Kondakova, Elena V., 372, 523
Konopliv, Alex, 947
KONUS (Russian Gamma Ray Spectrometer), 677, 869
Kopff comet, 739
Koptev, Yuri, 292, 297, 298, 565, 566
Korea, 21, 139
Kourou, French Guiana, 39
Kregel, Kevin R.
  STS-70, 369, 489
  STS-78, 371, 508
  STS-87, 373, 533
Krikalev, Sergei K.
  STS-60, 255, 367, 460
  STS-63, 300, 567
  STS-88, 277, 317, 374, 549
Krimigis, Stamatios, 806, 975
Kristall module, 266, 299–300, 497, 568
Kross, Deny, 210
Kunde, Virgil G., 973
Kunow, Horst, 877
Kurfess, James, 834
Kvant-1 module, 299–300, 303
Kvant-2 module, 299–300
Kwajalein, Marshall Islands, 885–86
Kyoto University, 863

L

Laboratoire de Recherche Spatiale, 867
Laboratory for Atmospheric and Space Physics (LASP), 605, 810
Laboratory for High Energy Astrophysics, Goddard Space Flight Center, 753
Laboratory for Space Astrophysics and Theoretical Physics, 687
Laboratory for Stellar and Planetary Physics, 877
Laboratory module, U.S., 284, 285, 288, 306, 308, 556, 557
Lacefield, Cleon, 183
Landessternwarte Heidelberg Research Group, 763
Langley Research Center
  Accelerometer, 959
  balloon flights, 909, 912, 915, 917
  Center of Excellence designation, 11
  crew return vehicle HL-20, 320
  GAS experiments, 493
  mission area, 11
  OEX program, 405
  RLV design and testing, 173, 174
  Scout ELVs, 58, 59
  sounding rocket program, 903
  Space Station Configuration Budget Review Team, 283
  SPACEHAB experiments, 252
  X-33 testing, 174, 175, 176
  X-34, 82
Lanzerotti, Louis J., 846, 933, 934
Large Angle and Spectrometric Coronograph (LASCO), 876
Large Isothermal Furnace (LIF), 470, 525
Large Orbiting Telescope, 621. *See also* Hubble Space Telescope
Large Space Telescope, 576
Las Campas Observatory, Chile, 622
Laser Geodynamic Satellite II (LAGEOS), 161, 249, 365, 435
Laser Image Detection and Ranging (LIDAR) System, 949, 970
Latitude/Longitude Locator (L3), 386
Launch and landing operations. *See* Space Shuttle: launch and landing operations
Launch and Mission Support, 92, 106–7
Launch Entry Suit/Advanced Crew Escape Suit (LES/ACES), 550
Launch Services, 13, 15, 35, 89, 90
Launch Services Purchase Act (LSPA), 37
Launch Site Equipment, 106
Launch systems
  budgets and funding for, 33–37, 89–117
  commercial and private sector development and building of, 21–22, 23
  development of, 19
  foreign, 23
  management of, 23–32
  national space policy and, 21–23, 80, 172
  types of, 19
Launch Vehicles division (Office of Space Access and Technology), 29
Launch Vehicles Office, 27, 29, 30, 97
Lawrence, Wendy B.
  STS-67, 369, 485
  STS-86, 373, 531
  STS-91, 374, 541
Lawrence Livermore National Laboratory, 724, 919, 948
LDB Subsystems, 907, 909, 911, 913, 917

Ledbetter, Kenneth, 585
Lee, Mark C.
  STS-30, 360, 379
  STS-47, 365, 429
  STS-64, 357, 368, 471, 475
  STS-82, 358, 372, 519, 520, 632
Leestma, David C.
  STS-28, 360, 380
  STS-45, 364, 420
Lemaire, Joseph, 848
Lenoir, William B., 24, 26, 203, 206, 282
Leonardo, 310–11
Lepping, R., 868
Leslie, Fred W., 369, 494
Levine, Alan, 802
Levine, Jack, 29
Lewis Research Center
  Centaur upper stage development, 70
  Center of Excellence designation, 11
  Cooperative Solar Array (CSA), 497
  GAS experiments, 493, 499, 507
  mission area, 11
  responsibilities of, 29
  Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET II), 857
  sounding rocket program, 897, 899, 900, 901, 902, 903, 905
  Space Station Work Package, 198, 201, 206, 207, 281, 552
  SPACEHAB experiments, 460
Lichtenberg, Byron K., 364, 420
Liesegang Rings Experiment, 434
Life and Biomedical Sciences and Applications Division (Office of Life and Microgravity Sciences and Applications), 211
Life and Microgravity Sciences and Applications, Office of (Code U)
  appropriations and functional areas, 12
  code letter designations, 193
  organization of, 211, 582, 586
  responsibilities of, 211, 582
  Space Shuttle/Spacelab Mission Management and Integration program, 196
  Space Station and *Mir* activities, funding for, 214
Life and Microgravity Spacelab (LMS), 163, 268, 354, 371, 509–11
Life Sciences Division (Office of Space Science and Applications), 210–11, 385, 575, 581
Life Sciences Flight program, 196
Life sciences missions. *See also* Spacelab
  budgets and funding for, 212, 330–31, 344–47
  management of, 210–12
Light Detection and Ranging (LIDAR) In-Space Technology (LITE), 162, 260, 368, 471
Limb Ozone Retrieval Experiment (SOLSE/LORE), 534
Limited Duration Space Environment Candidate Materials Exposure (LDCE), 428, 465
Lin, Robert, 868, 945
Lincoln Laboratory, Massachusetts Institute of Technology, 439, 858
Lindberg, Bob, 179
Lindsey, Steven W.
  STS-87, 373, 533
  STS-95, 374, 545
Linear Aerospike SR-71 Experiment (LASRE), 177, 178, 184
Linenger, Jerry M.
  aboard *Mir*, 234, 269, 270, 302, 517, 523, 524, 555
  STS-64, 368, 471
  STS-81, 269, 371, 517
  STS-84, 270, 372, 523, 524
Linhof camera, 470
Linkin, V. S., 970
Linnehan, Richard M.
  STS-78, 371, 508
  STS-90, 374, 538
Linteris, Gregory T.
  STS-83, 372, 521
  STS-94, 372, 525
Liquid Droplet Rotating-Collector Experiment, 434
Liquid Motion Experiment (LME), 524
Liquid Phase Electro-Epitaxy (LPEE), 452
Littles, Wayne, 30
Living With a Star initiative, 580
Lockheed Advanced Development Company, 85, 173
Lockheed Launch Vehicle (LLV), 41
Lockheed Martin Advances Technology Center, Space Physics Laboratory, 873, 874
Lockheed Martin Astronautics, 540
Lockheed Martin Corporation
  aerospike engines, 185
  Alpha Particle Spectrometer (APS), 945
  Athena ELVs, 41, 120, 121
  Atlas ELVs, 43, 131, 132, 134
  Cassini-Huygens, 973
  Centaur upper stage engine, 167
  ELV launch services, 38
  external tank, 165
  Hubble Space Telescope, 621, 824
  Ka-Band Solid-State Power Amplifier, 858
  Lunar Prospector, 944
  Mars Climate Orbiter, 968
  Mars Global Surveyor, 955
  Mars Polar Lander, 969
  merger with Martin Marietta, 41
  Multifunctional Spacecraft Structure, 859
  Polar, 871
  Power Activation and Switching Module, 859
  Shuttle processing work, contract for, 64–65
  Skunk Works, 85, 173, 176, 177, 178, 180, 181, 183, 184
  Space Station development, 294, 552
  Titan ELVs, 62, 158
  Transition Region and Coronal Explorer (TRACE), 812
  United Space Alliance (USA), 64
  X-33, 85–86, 87, 88, 171, 173, 176, 177, 178, 179, 180, 181, 183, 184, 185
  X-38 Crew Return Vehicle, 320
  Yohkoh/Solar-A, 879

Lockheed Martin Launch Vehicle (LMLV), 41
Lockheed Martin Missiles & Space
  sounding rocket program, 894
  Space Infrared Telescope Facility (SIRFT), 659
  Spitzer Space Telescope (Space Infrared Telescope Facility [SIRFT]), 659
Lockheed Martin Space Corporation, 888, 890, 893
Lockheed Missiles & Space Company
  functional cargo block (FGB), 308, 568
  Interim Control Module, 312, 568
  National Launch System, 79
Lockheed Palo Alto Research Laboratory
  Combined Release and Radiation Effects Satellite (CRRES), 820, 821
  Soft X-ray Telescope (SXT), 684
  Transition Region and Coronal Explorer (TRACE), 812
Logsdon, John, xxii
Long Duration Exposure Facility (LDEF), 159, 240, 241, 361, 385
Long-wave Radar, 964
Long-wavelength Infrared (LWIR) Camera, 949
Loop Heat Pipe/Sodium Sulfur Battery Experiment (LHP/NaSBA), 534
Lopez-Alegria, Michael E., 369, 494
Los Alamos National Laboratory
  Advanced Composition Explorer (ACE), 806
  Combined Release and Radiation Effects Satellite (CRRES), 821, 822
  High Energy Transient Experiment (HETE), 671
  Neutron Spectrometer (NS), 944
  Ulysses, 844
  Wide-field X-ray Monitor (WXM), 861
Lounge, John M., 362, 394
Low, G. David
  STS-32, 361, 385
  STS-43, 363, 409
  STS-57, 252, 356, 366, 449
Low Energy Concentrator Spectrometer (LECS), 854
Low Energy Ion Composition Analyzer (LEICA), 599, 797
Low Energy Transmission Grating (LETG) spectrometer, 657, 839–40
Low-energy Charges Particle Spectrometer, 965
Low-energy Particles (LEP) Experiment, 864–65
Lower Body Negative Pressure (LBNP) device, 414
Low-Power Electronics, 858
LTV Corporation, 59, 151
Lu, Edward Tsang, 372, 523
Lucent Technologies, 846
Lucid, Shannon W.
  aboard *Mir*, 267, 268, 272, 502, 512, 524, 555
  STS-34, 360, 382
  STS-43, 363, 409
  STS-58, 255, 366, 455
  STS-76, 267, 370, 502
  STS-79, 268, 371, 512
Lunar Prospector, 42, 119, 577, 715, 718–20, 772, 788, 938, 944–47
Lynn Lake, Canada, 908, 911, 913, 915, 916, 917, 918, 919, 920, 922, 924
Lyons, Michael T., 24, 26

M

M100 Spiral Galaxy, 623, 624
Macchetto, F. Duccio, 825
MacDowall, R. J., 845
MacLean, Steven G., 365, 435
Madagascar, 428
Madrid, Spain, 666
Magellan
  aerobraking, 697, 727
  characteristics, instruments, and experiments, 697–98, 699, 927–29; synthetic aperture radar (SAR), 694–95, 697, 928; windmill experiment, 697
  deployment of, 72, 75, 159, 239, 360, 379, 693–94, 767, 927; delay of, 577
  discoveries and scientific contributions from, 694–97, 698–99, 700, 701, 928–29
  funding for, 785
  IUS booster, 72, 75
  mission events, 926
  objective of, 577, 694, 767, 927
  orbit of, 694, 695–97
Magellanic clouds, 486, 614, 635, 636, 985
Magnetic Field Investigation (MFI), 868
Magnetic fields experiments
  Polar's Magnetic Fields Experiments (MFE), 680, 871
  Ulysses' Magnetic Fields Experiments (VHM/FGM), 844; Fluxgate Magnetometer (FGM), 844; Vector Helium Magnetometer (VHM), 844
Magnetic Fields Measurement (MGF), 865
Magnetic star SGR1900+14, 662
Magnetometer (MAG)
  Advanced Composition Explorer (ACE), 607, 808
  Galileo, 935
  Lunar Prospector, 945–46, 947
  Near Earth Asteroid Rendezvous (NEAR), 940
Magnetometer/Electron Reflectometer (MAG/ER), 726, 953, 956
Magnetospheric Imaging (MIMI) Mass Spectrometer, 975
Magnetospheric Ion Cloud Injection experiments, 619
Mahon, Joseph B., 24, 25
Main engines (SSME)
  Block I, 67, 264, 267
  Block II, 545
  Block IIA, 67
  budgets and funding for, 93, 106–7, 112
  characteristics of, 66–67, 69, 166, 215, 216, 350
  scrub or abort modes, 237, 238
Major League Baseball World Series game, 265
Majsuoka, Masuaru, 861
Makishima, Kazuo, 850, 880

Malerba, Franco, 247, 364, 427
Malin, Michael C., 952, 957, 968, 970
Malin Space Science Systems, Inc.
  Mars Color Imager (MARCI), 968
  Mars Descent Imager, 970
  Mars Observer Camera (MOC), 952, 957
Malina, Roger, 793
Malindi, Kenya, 855
Malmstrom Air Force Base, 86
Management and Budget, Office of, 6, 7, 586
Management Operations division (Office of Space Access and Technology), 29
Manipulator Flight Demonstration (MFD), 271, 529
Mansfield, John E,, 29
Mapping Radiometer, 964
Marangoni convection, 537
Marconi Space Systems, 741
Mariner 4 mission, 724
Mariner Mark II spacecraft, 739, 740, 741
Mars
  Astro-2, 755, 986
  Elysium Basin, 730
  "Face on Mars" image, 728, 729
  missions to, 575, 724–25, 735–36
  missions to, failure of, 576, 725, 953
  National Launch System and, 79
  Space Exploration Initiative, 576–77
  Valles Marineris, 730
  Viking Mars Lander missions, 397, 576, 724, 728, 966
Mars '94, 958
Mars '96 (Mars 8), 735, 771, 788, 958, 964–66
Mars Balloon Relay experiment, 725, 787
Mars Climate Orbiter, 141, 578, 725, 735, 736, 737–38, 773, 967–68
Mars Climate Orbiter Mission Failure Mishap Investigation Board, 738
Mars Color Imager (MARCI), 968
Mars Descent Imager, 970
Mars Global Surveyor, 139, 578, 724, 726–30, 771, 945, 954–59
Mars Observer, 155, 578, 714, 724, 725, 737, 769, 771, 785, 952–53
Mars Observer Camera (MOC), 726, 952, 957, 958
Mars Observer Laser Altimeter (MOLA), 726, 952, 955
Mars Oxidant Experiment, 735, 966
Mars Pathfinder
  budgets and funding for, 788
  Carl Sagan Memorial Station, 731
  characteristics, instruments, and experiments, 577, 578, 959, 960–63; Alpha Proton X-ray Spectrometer (APXS), 962; Atmospheric Structure Instrument/Meteorology Package (ASI/MET), 734, 961–62; Imager for Mars Pathfinder, 734, 961; wind socks, 962
  deployment of, 139, 772, 938, 960
  development of, 715
  discoveries and scientific contributions from, 731, 734–35, 963
  interest in, 578, 724
  lander, 734
  landing and landing site, 728, 731–32
  objective of, 772, 938
  Sojourner microrover, 578, 724, 731, 732–33, 962
Mars Polar Lander, 578, 725, 735, 736, 737, 739, 967, 969–70
Mars Relay Radio System, 726, 958
Mars Surveyor Operations Project, 735
Mars Surveyor Program, 587, 724, 726, 735–36, 789
Mars Surveyor Project '98 Office, 735
Mars Volatiles and Climate Surveyor instrument suite, 969–70
Marshall Space Flight Center
  Advanced X-ray Astronomical Facility (AXAF), 652, 838
  Astro-1, 751, 981
  Astro-2 home page, 263
  balloon flights, 909, 919, 921
  budgets and funding, 34
  Burst and Transient Source Experiment (BATSE), 646, 834
  Center of Excellence designation, 11
  Chandra (AXAF), 838
  CRESS management, 819
  Fastrac engine, 82, 83–84, 171, 176
  High Resolution Mirror Assembly, 654, 657
  Hubble Space Telescope, 626, 823
  IML-1, 244
  management of, 28, 30, 31
  mission area, 11
  Payload Operations Control Center, 196
  responsibilities of, 29
  solid rocket booster, 65
  sounding rocket program, 892, 901
  Space Shuttle Projects Office, 194, 195
  Space Station: air purification system testing, 309; management of, 204; Work Package, 198, 199, 206, 207, 281, 552
  Spacelab Center, 196
  Spacelab Management Office, 196
  Spacelab Mission Operations Control Center, 258, 270
  STS-35, success of, 398
  ultraviolet telescopes, aiming of, 396
  X-33, 175, 176, 178, 182, 185
  X-34, 82
  X-ray Calibration Facility, 654, 657
  Yohkoh/Solar-A, 879
Martin Marietta Corporation
  Advanced Launch System (ALS), 78
  Astronautics Group, 927
  Atlas ELVs, 43
  ELV launch services, 37, 38
  external tank, 65, 165
  merger with Lockheed Martin, 41
  Polar satellite, 674
  Titan ELVs, 61, 62, 72
  Wind, 674, 866
Mason, Glenn, 598, 797, 806
Mass Loss and Ion Composition, 848
Mass Spectrometer Telescope (MAST), 599, 797

Massachusetts Institute of Technology
  Advanced Satellite for Cosmology and Astrophysics (ASCA), 579, 851
  balloon flights, 907, 908
  Center for Space Research, 841
  High Energy Transient Experiment (HETE), 672, 860
  Lincoln Laboratory, 439, 858
  Low-Power Electronics, 858
  Magellan, 927
  NEAR Laser Rangefinder (NLR), 942
  Rossi X-ray Timing Explorer (RXTE), 802
  Solid-state Imaging Spectrometers (SISs), 851
  Ultraviolet CCD cameras, 861
Material in Devices as Superconductors (MIDAS), 268
Material Science Experiment Double Rack for Experimental Modules and Apparatus (MEDEA), 445
Materials Processing in Space budget category, 211
Mather, John, 791
Matra Marconi Space, 433, 875
Matra-Espace Corporation, 825
Matre/Laboratoire de Genie Electrique de Paris (L.G.E.P.), 468
Matsumoto, Hiroshi, 863
Mattingly, T. K., 174, 176
Maui, Hawaii, 377. *See also* Air Force Maui Optical System (AMOS) calibration test
Max Planck Institut für Aeronomie, 845, 969
Max Planck Institut für Extraterrestrische Physik
  Advanced Composition Explorer (ACE), 806
  BeppoSAX, 666
  Compton Telescope (COMPTEL), 835
  EGRET, 835
  Roentgen Satellite (ROSAT), 615, 817
  Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX), 598
Max Planck Institut für Kernphysik
  Cosmic Dust Analyzer (CDA), 873
  Dust Detector Subsystem (DDS), 935
  Dust Experiment (DUST), 847
Max Planck Institute
  Charge, Element, and Isotope Analysis System (CELIAS), 877
  Combined Release and Radiation Effects Satellite (CRRES), 820, 821
  Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX), 797
  Solar Ultraviolet Measurements of Emitted Radiation (SUMER), 876
Max Planck Institute for Chemistry, 962
May, Randy, 970
Mayo High School, Rochester, Minnesota, 529
Mazets, E., 869
McArthur, William S., Jr.
  STS-58, 366, 455
  STS-74, 370, 496
McCandless, Bruce, II, 361, 388
McClain, Gretchen, 30, 32, 209
McCleese, Daniel J., 953, 968
McComas, David, 806, 844
McCormick, Beth, 211
McCulley, Michael J., 360, 382
McCurdy, Howard, xxii
McDonnell Douglas Corporation
  Advanced Launch System (ALS), 78
  DC-X, 81, 169, 172
  DC-XA, 81, 173
  Delta ELVs, 49, 50, 51, 142, 143, 144
  ELV launch services, 37
  Geotail satellite, 675
  National Launch System, 79
  satellite launches: communication satellite for Germany, 138; communication satellites, 138; military communication satellite, 138
  Space Division, Huntsville, Alabama, 228
  Space Station: construction of components, 308; development of, 200, 208, 281, 296, 304, 552, 564; *Freedom*, termination of, 304
  X-33, 85, 173
McElroy, Michael, 936
McEntire, Richard, 863
McInerney, Pamela, 209
McKibben, R. B., 846
McMonagle, Donald R.
  STS-39, 362, 401
  STS-54, 365, 440
  STS-66, 368, 479
McMurdo Station, Antarctica, 907, 909, 911, 914, 916, 918, 919, 920, 922, 925
Meade, Carl J.
  STS-38, 361, 392
  STS-50, 364, 425
  STS-64, 357, 368, 471, 475
Measurement of Air Pollution from Satellites (MAPS), 256
Media and press kits, xxi, 238
Medium Energy Concentrator Spectrometer (MECS), 854
Medium-class Explorer missions (MIDEX), 592
  Imager for Magnetopause-to-Aurora Global Exploration (IMAGE), 592, 809
  Microwave Anisotrophy Probe (MAP), 592
Med-Lite launch vehicle, 592
Melnick, Bruce E.
  STS-41, 361, 390
  STS-49, 364, 422
Melnick, Gary J., 814
Mende, Steven, 820
Mendez, Mariano, 840
Merbold, Ulf D., 363, 415
Merit Badge Madness, 544
Mesoscale Lightning Experiment (MLE), 239, 379, 383, 386
Metals, Foamed Ultralight, 407
Meteorology Instrument System, 966
Meteorology instruments, 970
Metis, 711
Mewaldt, Richard, 798, 807
Meyers, Dale, 282
Michael Army Air Field, Dugway Proving Ground, Utah, 86
Michelson Doppler Imager/Solar Oscillations Investigation (MDI/SOI), 878

Michigan, 256
Microcapsules in Space (MIS), 439, 490
Microgravity Disturbance Experiment, 385
Microgravity Industry Related Research for Oil Recovery (MIRROR), 543
Microgravity Plant Nutrient Experiment (MPNE), 537
Microgravity Research program, 210
Microgravity Science and Applications Division (Office of Life and Microgravity Sciences and Applications), 211
Microgravity Science and Applications Division (Office of Space Science and Applications), 210, 211, 581
Microgravity Science Laboratory (MSL), 163, 164, 270, 354–55, 372
  MSL-1, 521, 522, 525–26, 527
Microgravity sciences
  budgets and funding for, 212, 331, 346
  GAS experiments, 407, 506
  LMS experiments, 510–11
  management of, 210–12
  SEM experiments, 548
Microgravity Sciences and Application Division, 210
Microgravity Sciences Division, 462
Microgravity Smoldering Combustion (MSC), 493, 507
MicroLab 1, 146
Microrover Flight Experiment, 732. *See also* Sojourner microrover
Microwave Anisotrophy Probe (MAP), 592
Midcourse Space Experiment (MSX), 513, 518, 519, 524, 527, 529
Middeck Active Control Experiments (MACE), 486
Middeck Glovebox Facility (MGBX), 501, 526, 533
Middeck Zero-Gravity Dynamics Experiment (MODE), 405, 411, 465
Middle Atmosphere High Resolution Spectrograph Investigation (MAHRSI) instrument, 271, 479
MightySat 1, 550
Military Application of Ship Tracks (MAST), 470, 472, 477, 490
Military Man in Space, 414
Milky Way galaxy, 613–14, 648, 650, 752, 754, 817, 836
Millcreek Township School District, 493
Millimeter Wave Atmospheric Sounder (MAS), 420, 441, 480
Millitech Corporation, 815
Miniature Camera and Imaging Spectrometer, 857
Miniature Sensor Technology Integration (MSTI), 147, 152, 668
MINISAT 01, 55, 147
Mir Environmental Effects Payload (MEEP), 272, 503, 504, 531
Mir Space Station
  accidents and system failures, 302–4, 531, 569
  astronaut training for, 232
  components, systems, and modules, 299–300; Androgynous Peripheral Docking Assembly, 293, 299, 300, 301, 568; Cooperative Solar Array (CSA), 497; Docking Module, 266, 496, 497, 504; European Space Agency (ESA), 532; Kristall, 266, 299–300, 497, 568; Kvant-1, 299–300, 303; Kvant-2, 299–300; Optical Properties Monitor, 274, 302; Piroda, 300; Reusable Solar Array (RSA), 497; Spektr, 272, 300, 303, 487, 489, 544, 568
  deployment of, 564
  Discovery STS-63, congratulations to from *Mir*, 482
  EVA, 234, 358, 504
  funding for flight activities, 35, 213–14, 327, 334–35
  International Space Station (ISS): development of, support for, 64, 191–92, 278; size compared to, 278
  return to Earth, 275n90
  safety concerns about, 304, 531
  Shuttle-*Mir* program, 301; agreements governing, 291–93, 297, 298, 565, 567; communication between *Mir* and STS-56, 250; compensation for cooperative program, 297, 298, 566, 567; knowledge and experience gained through, 278, 300; list of flights, 555; mission, goals, and objectives, 300; Orbiter Docking System, 220; orbiters capable of missions, 220, 221; rendezvous operations, practice for, 261, 262, 300, 481, 482, 484; return to Earth of *Mir* crew, 263–64, 268, 269, 270, 272, 274, 275, 293; STS-63, 300, 555, 567; STS-71, 162, 263–64, 300, 301, 302, 369, 487–88, 555; STS-74, 163, 266, 300–301, 370, 496, 497, 555; STS-76, 163, 266–67, 370, 502, 504, 555; STS-79, 163, 268, 371, 555; STS-81, 163, 269, 371, 555; STS-84, 164, 270, 372, 555; STS-86, 272, 273, 304, 373, 531–32, 555; STS-89, 164, 274, 373, 536–37, 555; STS-91, 164, 275, 374, 541–44, 555
  solar array, 308
  Solar Array Cap, 272
  Space Station program and, 291–93, 294, 297
  SPACEHAB as support for, 228, 267, 268, 272, 273, 274, 275, 503, 513, 517, 523–24, 531, 536, 541
  Spacelab research and payloads, 191, 196, 229, 354, 488
  U.S. astronauts aboard, 64, 191, 234, 263–64, 267, 268, 269, 270, 272, 274, 275, 278, 292, 293, 300, 303, 304, 502, 512, 517, 523, 531, 536, 555; EVA, 234, 302, 303; time spent aboard *Mir*, 64, 268, 269, 270, 272, 274, 275, 278, 293, 300, 488, 524, 555
Mission and Payload Development Division (Office of Space Science), 585
Mission and Science Operations Center, Berkeley, California, 602
Mission Communication Services, 14
Mission Management Office, 196
Mission Operation Reports, xxi

Mission Peculiar Equipment Support Structure (MPESS), 351
Mission Research Corporation, 904
Mission Science Office, 196
Mission Support (MS) appropriations, 6, 14
Mission to Planet Earth, Office of, 13
Mission to Planet Earth program (Code Y), 214, 250, 260, 582
Mitre Corporation, 407
Mixed fleet strategy, 21, 575
Mobile Servicing Systems, 279, 556
Möbius, Eberhard, 807
Mohri, Mamoru, 365, 429
Monrovia Elementary School, Madison, Alabama, 548
Montello High School, Montello, Wisconsin, 548
Moog, Inc., 856
Moon
  Clementine, 156, 720–24, 769, 948–51
  images of, 485
  Lunar Prospector, 42, 119, 577, 715, 718–20, 772, 788, 938, 944–47
  National Launch System and, 79
  Space Exploration Initiative, 576–77
Moore, Thomas E., 873
Moorehead, Robert W., 203
Moos, H. Warren, 615
Morgan State University, 475
Morocco, 237
Moron, Spain, 237
Moroz, Vassili, 968
Morrison, David, 936
Moscow, Russia, 298
Moscow High School, Idaho, 543
Moscow University, Idaho, 543
Moser, Thomas L., 203
Motorola Government Space System, 858
Mozer, Forrest S., 872
Mukai, Chiaki, 374, 545
Mukai, Toshifumi, 864–65
Mullane, Richard M., 361, 387
Multichannel Optical Spectrometer, 964
Multifunctional Spacecraft Structure, 859
Multimission Archive, Space Telescope Science Institute (STScI), 687, 689
Multiple Experiment Transporter to Earth Orbit and Return (METEOR), 47–49
Multi-Purpose Experiment Canister (MPEC), 380, 402
Multi-Purpose Logistic Modules, 280, 310
Multispectral Imager (MSI), 939–40
Murray, Stephen, 839
Musgrave, F. Story
  STS-33, 360, 384
  STS-44, 363, 413
  STS-61, 236, 357, 367, 458, 459, 628, 629
  STS-80, 371, 514, 516

N

Nagai, Tsugunobu, 865
Nagel, Steven R.
  STS-37, 362, 399
  STS-55, 366, 444
Naito-Mukai, Chiaki, 258, 367, 469
Nanocrystal Get Away Special (NANO-GAS), 507
Narrow Angle Camera (NAC), 974
Narrow Field Instruments, 854–55
NASA Historical Data Book, 1979-1988, Volume V, 215
NASA Historical Data Book, 1989-1998, Volume VIII, 5, 238, 574
National Academy of Sciences
  Astronomy Survey Committee, 613
  Board on Physics and Astronomy, 659
  National Research Council, 658
  Space Science Board, 740
National Advisory Committee for Aeronautics (NACA), 3
National Aeronautics and Space Act, 3, 573
National Aeronautics and Space Administration (NASA)
  achievements of, 3
  administrators of, 24, 27, 80, 206, 211, 282, 291, 565, 576, 577, 582, 584
  Advisory Council, 314, 570
  budgets and funding process, 5–8, 33–34, 212, 215n42
  Centers of Excellence, 4, 11, 583–84
  code letter designations for organization, 192–93
  creation of, 3
  direction of, groups that influence, 3–4
  "faster, better, cheaper" concept, 577, 582, 587–88, 714, 718, 737, 772
  Gray Beards panel, 180
  management and organization of, 23–32, 192–93
  mission, goals, and objectives, 573, 574
  mission of, 3
  mixed fleet strategy, 21, 575
  Monographs in Aerospace History No. 9, 238
  national space policy and, 22–23, 80
  overview of, 4
  Program Committment Agreement, 674
  Program Management Council, 674
  reorganization of, 582
  RLV Technology program, 80, 172
  Space Launch Initiative, 84, 88
  Strategic Enterprises, 30
  Strategic Plan, 583
  Ultralight launcher, 55
  Web sites for programs and projects, xxi, xxii, 574
National Aeronautics and Space Administration (NASA) Centers. *See also specific centers*
  budgets and funding, 6
  Center of Excellence designations, 4, 11
  mission and focus of, 4, 11
  overview of, 4
National Aeronautics and Space Administration (NASA) Headquarters
  downsizing and restructuring of, 32
  GAS experiments, 434
  overview of, 4

  Pool Boiling Experiment, 452, 462
  sounding rocket program, 898
  Space Station, Office of (Code S), 197, 198, 203, 206
  Space Systems Development, Office of (Code D), 206
  Spacelab management, 196
National Aeronautics and Space Administration (NASA) History Division, xxii
National Aerospace Plane (X-30), 79–80
National Astronomical Observatory, Japan, 684, 880
National Center for Atmospheric Research, 757, 897, 902
National Center for Scientific Research (CNRS), 876
National Institute of Standards and Technology (NIST), 540, 684
National Institutes of Health
  Neurolab mission, 274
  NIH-C, 468, 483, 490, 515
  NIH-R, 480, 490, 498, 515
National Launch System, 26, 77, 78–79
National Oceanic and Atmospheric Administration (NOAA)
  Launch Vehicles Office and, 29, 97
  ozone measurements, 246, 382, 480
  Real Time Solar Wind (RTSW) Data Experiment, 808
  reports from, 190, 574
  satellites, 122, 123, 124, 125
  Space Environment Center, 808
National Optical Astronomy Observatories, 934
National Research Council
  Astronomy and Aerophysics Survey Committee (AASC), 658
  Committee on Astronomy and Astrophysics, 659
  Space Studies Board, 288, 659
  "Strategy for Space Astronomy and Astrophysics for the 1980s," 658
National Research Laboratory. *See* Lawrence Livermore National Laboratory
National Science and Technology Council, 3
National Science Foundation, 274, 888
National Scientific Balloon Facility, 908, 909, 910, 911, 913, 918, 920, 921, 923, 924
National Scientific Balloon Facility, Texas, 693, 694, 906, 907
National Space Council, 3, 78, 290, 565
National Space Development Agency of Japan (NASDA), 270, 279, 280, 429–32, 470
National space policy
  development of, 3
  launch systems and, 21–23, 80, 172
  Space Exploration Initiative, 576–77
National Space Science Data Center (NSSDC), xxiii, 238
National Space Transportation Policy, 22–23, 80, 172
National Space Transportation System (Office of Space Flight division), 24–25, 193
Naval Postgraduate School, 381, 418
Naval Research Center, 893
Naval Research Laboratory, U.S.
  balloon flights, 920
  Bragg Crystal Spectrometer (BCS), 684, 880
  Clementine, 724
  Combined Release and Radiation Effects Satellite (CRRES), 820
  Far Ultraviolet Imaging Spectrograph (FUVIS), 761, 774
  GAS experiments, 503
  Large Angle and Spectrometric Coronograph (LASCO), 876
  Oriented Scintillation Spectrometer Experiment (OSSE), 646, 834
  sounding rocket program, 883, 884, 886, 889, 890, 891, 894, 898, 903, 904
  tracking station, Pomonkey, Maryland, 950
Naval Research, Office of, 274
NAVSTAR Global Positioning System (GPS) satellites, 50, 51, 136–40
Navy, U. S.
  Naval Postgraduate School, 381, 418
  Polaris missiles, 58
  Project Pilot, 51
  satellites, 123, 124, 146
  Vanguard missiles, 58
Near Earth Asteroid Rendezvous (NEAR), 139, 577, 578, 679, 715–18, 770, 788, 938, 939–43
Near Earth Asteroid Rendezvous (NEAR) Shoemaker, 717
Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 358, 519, 630, 632, 831–32
Near Infrared Spectrometer (NIS), 940
NEAR Laser Rangefinder (NLR), 942
Near-infrared (NIR) CCD Camera, 949
Near-infrared Mapping Spectrometer (NIMS), 934
NEC, 849
Nephelometer (NEP), 709, 933
Neptune, 746, 748–49, 980
Ness, Norman, 807
Net Flux Radiometer (NFR), 709, 933
Netherlands. *See also* Compton Gamma Ray Observatory (CGRO)
  ATLAS-1 instruments, 246
  BeppoSAX, 125, 578, 666, 771
  Capillary Pumped Loop (CAPL), 462
  Compton Telescope (COMPTEL), 646
  ESA membership, 279
  European Space Research and Technology Centre, Noordwijk, Netherlands, 451
  International Solar-Terrestrial Physics (ISTP) program, 672
  Italian-Dutch telescope, 40, 125
  TRACE, 608, 812
Netherlands Institute for Space Research, 840
Neurolab mission, 164, 274–75, 355, 374, 538–39
Neutron Spectrometer (NS), 944, 965
New Jersey Institute of Technology, 924
New Launch System, 78–79, 101
New Mexico State University, 468, 906, 911, 916, 917, 921, 923, 924
New Millennium Program
  budgets and funding for, 587

    Deep Space 1, 141, 667, 668–69, 670, 773, 856–59
    Deep Space 2, 739
    funding for, 789
    launch of, 141
    management of, 667
    objectives of, 667
    Students for the Exploration and Development of Space (SEDSAT), 141, 667, 669–71, 773, 859
New South Wales, Australia, 716
New Zealand, 910, 914
Newman, James H.
    dogtag, 265
    STS-51, 253, 357, 366, 453
    STS-69, 265, 369, 491
    STS-88, 277, 316–17, 319, 359, 374, 549
NGC 4151, 984
NGC 4603 spiral galaxy, 641, 642
Nicholson, Leonard S., 26, 27
Nicogossian, Arnauld, 211
Nicollier, Claude
    STS-46, 364, 427
    STS-61, 367, 458, 459
    STS-75, 370, 500
Niemann, Hasso B., 933, 979
Nishimura, Jun, 881
Nissho Iwai American Corp., 407, 408
Noci, Giancarlo, 848
Norfolk, Virginia, Public Schools (NORSTAR), 473, 515, 544
Noriega, Carlos I., 372, 523
NORSTAR (Norfolk, Virginia, Public Schools), 473, 515, 544
North Carolina, 256
North Carolina A&T State University, 477
Northrop Grumman, 838
Norway, 140, 279, 672
Norwood, Robert, 29
NPO-Energia, 292–93, 312, 565, 569
NSPO/RDD, 936
NSSDC (National Space Science Data Center), xxiii
NSTS Shuttle Reference Manual, 215
Nucleic Boiling, 543

O

Occhialini, Giuseppe, 666
Occupational Health and Aerospace Medicine Division (Office of Life and Microgravity Sciences and Applications), 211–12
Occupational Health Office, 211
Ochoa, Ellen
    STS-56, 365, 441
    STS-66, 368, 479
O'Connor, Bryan D.
    administrative positions, 27, 28, 30, 208, 294
    STS-40, 362, 403
Odom, James B., 203, 282
Ogilvie, K., 867
Olin-Sang-Ruby Union Institute, 544
Olympic Torch Relay, 508
OMNI International, Ltd., 407
Omnidirectional Ionospheric Energy-mass Spectrometer, 965
Opal, Hurricane, 494
Open data policy, 608
Optical Coating Laboratory, Inc., 654
Optical Communications Through Windows (OCTW), 409
Optical Control Electronics Enhancement Kit, 520
Optical Properties Monitor, 274, 302
ORBCOMM communication satellites, 55, 146, 147, 148, 154
Orbital Acceleration Research Experiment (OARE), 405, 457, 470, 495, 500
Orbital Ball Bearing Experiment (OBBEX), 406, 462
Orbital Debris Radar Calibration System (ODERACS), 439, 462, 483
Orbital maneuvering vehicle, 89, 91, 99
Orbital Sciences Corporation
    ELV launch services, 37
    Pegasus ELVs, 51, 55, 146, 149, 150, 592–93
    Taurus ELVs, 59, 153
    X-34, 82, 83, 84, 171, 172, 173, 177, 180, 186
Orbiter
    budgets and funding for, 92, 104–5, 111
    characteristics of, 215, 216, 217–19, 349–50
    extended duration orbiter, 92, 105, 219, 247, 255, 354–55, 414, 470, 486, 495, 511, 522, 527, 540
    glass cockpit, 221
    management of, 65
    modifications and upgrades to, 219–21, 258, 425
    Orbiter Docking System, 220, 229–30
Orbiter Experiments Autonomous Supporting Instrumentation System (OASIS-I), 376
Orbiter Experiments Program (OEX), 219, 396, 405
Orbiter Maintenance Down Period (OMDP), 219, 220–21, 249, 519, 536
Orbiter Space Vision System (OSVS), 271
Orbiter Stability Experiment, 408, 462, 475
Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph-Shuttle Pallet Satellite (ORFEUS-SPAS)
    characteristics, instruments, and experiments, 762, 763–66, 988; Extreme Ultraviolet (EUV) Spectrograph, 763–64, 765, 988; Far Ultraviolet (FUV) Spectrograph, 763–64, 765, 766, 988; Interstellar Medium Absorption Profile Spectrograph (IMAPS), 269, 764, 765, 766, 988; Remote IMAX Camera System (RICS), 764–65; Surface Effects Sample Monitor (SESAM), 269, 271, 764, 765, 988
    discoveries and scientific contributions from, 765–66
    ORFEUS-SPAS I, 161, 253–54, 366, 454, 763–66, 774
    ORFEUS-SPAS II, 163, 269, 371, 515, 766, 775
Orbiting Astronomical Observatories, 621

Oriented Scintillation Spectrometer Experiment (OSSE), 645, 646, 650, 834, 836
Origin and Distribution of Life in the Universe theme, 583
Orsini, Stefano, 861
Orton, Glenn S., 936
Oswald, Stephen S.
  STS-42, 363, 415
  STS-56, 365, 441
  STS-67, 369, 485
Ottobrunn high school, Germany, 766
Out of Ecliptic, 660
Outreach office (Office of Space Flight), 32
Owen, Tobias, 936

P

Pacific Ocean, 471, 606, 651, 735
Palestine, Texas, 693, 694, 906, 908–13, 915, 917–24
Panoramic Camera, 966
Parazynski, Scott E.
  STS-66, 368, 479
  STS-86, 272, 373, 531
  STS-95, 374, 545
Paris, France, 297, 566
Paris Observatory, 978
Parise, Ronald A.
  STS-35, 242, 362, 394
  STS-67, 369, 485
Parker, Robert A. R.
  Space Flight/Space Station Integration Office, 203
  STS-35, 242, 362, 394
Parks, George K., 873
Particle Physics and Astronomy Research Council (British Science and Engineering Research Council), 687
Passive Aerodynamically Stabilized Magnetically Damped Satellite (PAMS), 267
Passive Common Berthing Mechanism, 315
Pawelczyk, James A., 374, 538
Payload and Instrument Development, 780
Payload and Utilization Operations appropriations, 15, 33, 35, 89, 90, 91, 94, 96
Payload assist module (PAM), 69, 70, 71, 219, 241, 390, 505
Payload operations and support equipment funding, 98
Payload Operations Control Center, Marshall Space Flight Center, 196
Payton, Gary, 29, 32, 174, 178, 181, 182, 183
Pearson, Jeremiah W., III, 27, 30, 206, 208
Pegasus ELVs
  acquisition of, 37
  characteristics of, 20, 56–57, 149–50
  development of, 51, 55
  launch sequence, 57–58
  launches with, 21, 38–40, 55–57, 118, 146–48, 592–93, 671
  management of, 29
  payloads, 57, 146–48
  as Scout replacement, 59
  success rate for launches, 38, 118
Pellerin, Charles J., 581, 582
Pennsylvania State University
  Advanced Charged Couple Imaging Spectrometer (ACIS), 839
  balloon flights, 920, 921, 922, 923
  Cosmic Unresolved X-ray Background Instrument Using CCDs (CUBIC), 861
  GAS experiments, 506
  sounding rocket program, 884, 885, 888, 895, 899, 902, 904, 905
Perkin-Elmer Corporation, 623, 652, 828
Permittivity and Electromagnetic Wave Analyzer, 978
Perry, Thomas, 581
Peru, 606
Peterson, William K., 821, 873
Pettengill, Gordon, 927
Philippines, 21
Phillips Laboratory, Kirtland Air Force Base, 80, 175, 859
Phobos, 730
Phoswich Detection System (PDS), 855
Photogrammetric Appendage Structural Dynamics Experiment (PASDE), 496
Photopolarimeter Radiometer (PPR), 934
Physical Sciences, Inc., 856
Physical-Meteorological Observatory, 878
Physics and astronomy budget category, 586, 589, 776, 777, 778–84
Physics missions, 577, 584. *See also* Astrophysics missions; Solar physics missions; Space physics missions
Physiological and Anatomical Rodent Experiment (PARE), 412, 440, 443, 480, 490, 498
Pilcher, Carl, 585
Pillan Patera, 713
Pilot Inflight Landing Operations Trainer (PILOT), 457
Pinkau, K., 835
Pioneer missions
  areas explored by, 661, 740
  discoveries and scientific contributions from, 575, 739, 745–48
  Pioneer 6, 744
  Pioneer 10, 744–46, 750, 980
  Pioneer 11, 744, 745, 746
  Pioneer Venus (Pioneer 12), 747–48
  plaque for communication with intelligent species, 746–47
  Radioisotope Thermoelectric Generators (RTGs), 741
Piotrowski, William L., 582, 584
Piroda module, 300
Pituitary Growth Hormone Cell Function (PHCF), 428
PKS2155-304, 765
Planetary exploration budget category, 577–78, 584, 586, 767, 769, 770, 771, 772, 773, 776, 777, 784–89
Planetary Fournier Spectrometer, 964
Planetary Observer program, 714
Planetary Science and Astrophysics, Office of

(Code S), 582
Planetary System Origin and Evolution theme, 583
Planets, year of the, 575
Plants and seeds exposure to space, 258, 383, 407, 408, 430, 433, 473, 475, 507, 530, 532, 534, 537, 548. *See also* ASTROCULTURE; Chromosome and Plant Cell Division in Space Experiment (CHROMEX)
Plasma Experiment for Planetary Exploration (PEPE), 858
Plasma Investigation Subsystem (PLS), 935
Plasma Motor Generator, 76–77, 138
Plasma Source Instrument (PSI), 680, 873
Plasma Wave Investigation (PWI), 680, 863, 872
Plasma Wave Subsystem (PWS), 935
Pluto, 746
Poker Flat Research Range, 882, 884–87, 889–95, 897–900, 902
Polar, 50, 139, 579, 672, 673, 674, 675, 676, 770, 809
Polar Ionospheric X-ray Imaging Experiment (PIXIE), 679, 680, 874
Polar Lander. *See* Mars Polar Lander
Polar satellite, 679–80
Polaris missiles, 58
Polymer Morphology (PM), 383
Pomonkey, Maryland, 950
Pongratz, Morris, 821
Poniatowski, Karen, 30, 32
Pool Boiling Experiment, 434, 452, 462, 499, 507
Popcorn experiments, 473, 507, 515, 543
Poquoson Middle School, Poquoson, Virginia, 515
Porco, Carolyn C., 974
Postal Service, U.S., 260, 477
POSTAR, 433
Post-spaceflight orthostatic intolerance, 550
Pounds, Kenneth, 817
Power Activation and Switching Module, 859
Prairie View A & M University, 924
Pratt & Whitney
    Athena ELVs, 41, 120, 121
    Atlas ELVs, 128, 129, 131, 132, 134
    Centaur upper stage engine, 70, 71, 167
Precision Gamma Spectrometer, 966
Precourt, Charles J.
    STS-55, 366, 444
    STS-71, 369, 487
    STS-84, 372, 523
    STS-91, 374, 541
President of the United States. *See also* Bush, George H. W.; Clinton, William J.; Reagan, Ronald
    Advisory Committee on the Future of the U.S. Space Program, 287, 564
    Aeronautics and Space Reports of, xxi
    budgets and funding process, 7
    policy development by, 3
    space science missions, funding for, 586
    Space Station, funding for, 213, 286–87
    United States Presidential Award for Design Excellence, 689
Press and media kits, xxi, 238
Press releases, xxi–xxii
Pressure Modulator Infrared Radiometer (PMIRR), 953, 968
Primex Technologies, 41, 120, 121
Prince Albert, Canada, 906
Princeton University, 920, 921
Principal Investigator (PI), 579, 580, 590, 714–15
Program Committment Agreement, 674
Program Integration Division (Office of Space Communication), 32
Program Management Council, 674
Program Operating Plan, 6
Programs and projects, NASA
    definition, 5
    formulation, 5
    functional areas, 4, 9–10
    funding for, 5
    implementation, 5
    life cycle phases, 5
    office designations, 4, 9–10
    Web sites for, xxii, xxiii
Progress resupply vehicle, 280, 299, 303
Project Pilot, 51
Proportional Counter Array (PCA), 600, 602, 801, 802, 803
Protein Crystal Growth (PCG) experiments, 378, 385, 430
    Advanced PCG (APCG), 465
    Commercial PCG (CPCG), 423, 437, 454, 465, 470, 477, 483, 490, 498, 501, 532
    GAS experiments, 499
    PCG III, 389, 410
    PCG-II-2, 412
    PCG-STES (Single Locker Thermal Enclosure System), 480, 483, 486, 498, 524, 529, 547
    PCG-TES (Thermal Enclosure SYstem), 480, 486
Protein Crystallization Apparatus, 526
Protein Crystallization Facility (PCF), 399, 423
Protein studies (PSE), 391, 437, 465
Proton/Electron Telescope (PET), 599, 798
Pudwill-Gorie, Dominic L., 374, 541
Puppis A, 985
Purdue University, 515, 544

Q

Quadrupole Mass Spectrometer, 965
Quasars, 640, 648, 836
Quayle, Daniel, 21, 78, 290, 291, 565
QUESTS, 434

R

Radiation Monitoring Equipment (RME), 380, 384, 387, 389, 391, 399, 402, 414, 417, 421, 439, 440, 454, 472, 490, 503, 524
Radiation/Dosimetry Control Complex, 966
Radio and Plasma Wave Experiment (WAVES), 867, 869
Radio and Plasma Wave Science (RPWS) instru-

ment, 976
Radio Atmospheric Science Center, Kyoto University, 863
Radio Detection and Ranging (RADR) instrument, 975
Radio Science
  Celestial Mechanics, 936
  Propagation, 936
Radio Science Experiments, 942, 953, 956
Radio Science Subsystem (RSS), 976
Radioisotope Thermoelectric Generators (RTGs), 383, 660, 664, 741–42
Radish experiments, 473, 543
Rafaello, 310
Ragent, Boris, 933
Rahe, Jurgen, 584, 585
RCA, 552
R-Cubed Composites, 61
Readdy, William F.
  administrative position, 32
  STS-42, 363, 415
  STS-51, 366, 453
  STS-79, 371, 512
Reagan, Ronald
  Challenger accident investigation, 190
  space policy of, 3, 22
  Space Shuttle payloads, 49
  Space Station *Freedom*, 191, 213, 277, 280, 282, 564
Real aperture radar, 695
Real Time Solar Wind (RTSW) Data Experiment, 808
Reck, Gregory, 27
Redlands, California, Unified School District, 408
Reeves, Edmond, 211
Reightler, Kenneth S., Jr.
  STS-48, 363, 411
  STS-60, 367, 460
Reilly, James F., 373, 536
Reilly, Michael, 32
Research and Development (R&D) appropriations
  launch systems, 33, 34, 35
  programmed budget, 91–92, 94, 327–31
  programs funded with, 6, 9–10, 12–14, 89, 90
  Space Station program, 213, 215, 324–26
  Spacelab, 212
Research and Program Management (R&PM) appropriations, 6
Research Animal Holding Facility (RAHF), 231–32
Research Program Management (Office of Space Science), 584, 585
Reston, Virginia, 197, 198, 203, 206, 208, 296
Reusable launch vehicles (RLVs). *See also specific programs*
  budgets and funding for, 36, 91, 102
  chronology, 172–86
  commercial and private sector development and building of, 23
  development of, 21, 22, 29, 79–80
  responsibility to develop, 22, 32, 80
  RLV Technology program, 80, 172
  Space Shuttle as, 20
  study to support use of, 183
Reusable Solar Array (RSA), 497
Rhome, Robert, 211
Rice University, 916, 918, 919
Richards, Richard N.
  STS-28, 360, 380
  STS-41, 361, 390
  STS-50, 364, 425
  STS-64, 368, 471
Ricker, George, 851, 861
Rieder, Rudolph, 962
RIKEN, 861
Rising, Jerry, 176, 179, 183
Roach experiment, 547
Robbins, C. Howard, Jr., 26, 205
Robert Gordon University, Aberdeen, Scotland, School of Electronics and Electrical Engineering, 507
Robinson, Stephen K.
  STS-85, 373, 528
  STS-95, 374, 545
Robot Operated Materials Processing Systems (ROMPS), 472
Rocketdyne
  aerospike engines, 184, 185
  Atlas ELVs, 127, 128, 129, 131, 132, 134
  Delta ELVs, 142, 143, 144
  Orbiter Maintenance Down Period (OMDP), 479
  purchase of, 65n69
  Space Shuttle, 65, 166, 219
  Space Station: construction of components, 308, 309; development of, 208, 281, 296, 304, 552, 564; *Freedom*, termination of, 304
  X-33, 171, 175, 177, 178, 179, 183
Rockwell International Corporation. *See also* Rocketdyne
  Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 831
  purchase of, 65n69
  Space Shuttle modifications and upgrades, 219
  Space Shuttle orbiters, 65
  Space Shuttle processing work, contract for, 64–65
  United Space Alliance (USA), 64–65
  X-33, 85, 173
  X-38 Crew Return Vehicle, 320
Roentgen Satellite (ROSAT), 136, 579, 593, 615–18, 767, 816–18
Rogers Commission, 190
Rohr, 171, 177
Rohrabacher, Dana, 181
Rominger, Kent V.
  STS-73, 369, 494
  STS-80, 371, 514
  STS-85, 373, 528
Room Temperature Vulcanizing, 491
Ross, Jerry L.
  STS-37, 242, 356, 362, 399, 400
  STS-55, 366, 444
  STS-74, 370, 496
  STS-88, 277, 316–17, 319, 359, 374, 549
Rossi, Bruno, 599

Rossi X-ray Timing Explorer (RXTE), 139, 579, 599–600, 602, 650, 770, 781, 790, 801–3
Rotating Dome Experiment, 456
Rothenberg, Joseph H., 32, 210
Rothschild, Richard, 802
Roux, Alain, 936
Runco, Mario, Jr.
  STS-44, 363, 413
  STS-54, 249, 356, 365, 440
  STS-77, 370, 505
Russell, Christopher T., 871, 936
Russia and Russian Space Agency. *See also Mir* Space Station; Soyuz vehicle; United States-Russian Cooperative Program
  Androgynous Peripheral Docking Assembly, 293
  astronauts on STS-74, 266
  creation of Russian Space Agency, 291–92, 565
  International Space Station (ISS): agreements governing, 314–15, 569; compensation for cooperative program, 297, 298, 566, 567; contributions to, 280, 305, 306, 307, 308, 313, 556, 567, 568; development of, 191, 192, 197, 277, 278; funding for, 213, 314; management of activities, 209, 210; *Mir* missions in support of, 191–92; partner status of, 297–98, 306, 312, 566–67; political and financial problems, 213, 305, 311–12, 314, 568; Zarya module, 192, 277, 278, 280, 315, 316–17, 319–20, 561, 562–63, 570
  IUE observers, 688
  KONUS (Russian Gamma Ray Spectrometer), 677, 869
  Laser Image Detection and Ranging (LIDAR) System, 970
  LIDAR LITE experiment, 471
  Mars '94, 958
  Mars '96 (Mars 8), 735, 771, 958, 964–66
  missile technology to India, 297, 566
  Progress resupply vehicle, 280, 299, 303
  Salyut space stations, 298–99
  satellites, 141
  SIR-C/X-SAR imaging, 477
  Space Station *Alpha*, 297
  Zarya module, 549
Russian Cooperation and Program Assurance account, 214
Russian Program Assurance budget category, 312
Rutherford Appleton Laboratory, 875
Ryumin, Valery Victorovitch, 374, 541

S

S-19 Boost Guidance System, 692
Sacco, Albert, Jr., 369, 494
Safety, Reliability, and Quality Assurance, Office of, 14
Safety, Reliability, Maintainability, and Quality Assurance, Office of, 10
Safety enhancements, 89
Sagan, Carl, 936
Sahara desert, 428
Sakana Seeds Corp., 407
Salyut space stations, 298–99
Sample Return Experiments, 452, 460, 461, 475, 478, 492, 493
San Francisco Bay Area, California, 388
San Jose State University, 961
Sanders, 184, 185
Satelite de Aplicaciones Cientifico-A (SAC-A), 164, 549
Satelite de Aplicaciones Cientifico-B (SAC-B), 147, 148, 576, 671, 672, 771, 860–61
Satellite Test Unit (STU), 505
Saturn
  Cassini-Huygens, 61, 63, 156, 576, 740–44, 772, 971–79
  missions to explore, 575, 740
  objectives of Cassini-Huygens, 971–72
  Pioneer missions, 746
  Voyager missions, 748, 980
S-band Transponder Doppler Gravity Experiment, 950
Scaled Composites, 321
Scherrer, Philip, 878
Schlegel, Hans W., 366, 444
Schmitz, Robert, 211
Schofield, John T. "Tim," 961
Scholer, M., 797
Schönfelder, Volker, 835
Schubert, Gerald, 936
Science, Aeronautics, and Technology (SAT) appropriations
  launch systems, 33–34, 35, 36
  programmed budget, 91–92, 94, 95
  programs funded with, 6, 12–14, 89, 90
  Space Station program, 213–14, 215
Science, Applications, and Technology appropriations, 35
Science and Engineering Research Council, Great Britain, 616, 684
Science and Technology Policy, U.S. Office of, 294
Science Applications International Corporation (SAIC), 890
Science Data Center, 715
Science Instrument Module (SIM), 657
Science Operations Center, 600
Science Power Platform, 280
Science Program Committee, European Space Agency (ESA), 740
Science Working Group, 714
Scientific Applications Satellites. *See* Satelite de Aplicaciones Cientifico-A (SAC-A); Satelite de Aplicaciones Cientifico-B (SAC-B)
Scientific Balloon Flight Facility, New Mexico, 693
Scorpius, 649
Scott, Winston E.
  STS-72, 358, 370, 498, 499
  STS-87, 359, 373, 533, 535
Scout ELVs
  characteristics of, 20, 58, 151
  launches with, 19, 21, 38–39, 58–59, 118, 152
  success rate for launches, 38, 118

Scudder, Jack, 872
Searfoss, Richard A.
  STS-58, 366, 455
  STS-76, 370, 502
  STS-90, 374, 538
Seddon, Margaret Rhea
  STS-40, 362, 403
  STS-58, 366, 455
Seeds exposure to space, 407, 408, 433, 473, 475, 507, 532, 548
Sega, Ronald M.
  STS-60, 367, 460
  STS-76, 370, 502
Seiff, Alvin, 933, 961
Seismometer, Magnetometer, and Inclinometer, 966
Semiconductor experiments, 408, 451, 472, 507, 543
Sensor Technology Experiment (STEX), 154, 383
Sergeant surface-to-surface missiles, 58
Serlemitsos, Peter J., 849, 983
Service d'Aeronomie du Centre National de la Recherche Scientifique, 979
SGR1900+14 magnetic star, 662
Sharipov, Salizhan Shakirovich, 373, 536
Shaw, Brewster H., Jr
  administrative position, 27
  STS-28, 360, 380
Shawhan, Stanley, 581
Shea, Joseph, 294, 565
Shepherd, William M.
  administrative positions, 208, 209
  STS-41, 361, 390
  STS-52, 365, 435
Sherlock, Nancy J. (Currie)
  STS-57, 366, 449
  STS-70, 369, 489
  STS-88, 277, 317, 374, 549
Shishkin, Oleg, 291, 565
Shoemaker, Eugene M., 717, 948
Shoemaker-Levy 9 comet, 634, 635, 706, 707, 717, 930, 937
Shoreham Wading River High School, New York, 544
Shoshone-Ba Junior/Senior High School, Fort Hall Reservation, Idaho, 543
Shriver, Loren J.
  STS-31, 361, 388
  STS-46, 364, 427
Shuttle Activation Monitor (SAM), 381, 411, 414
Shuttle Amateur Radio Experiment (SAREX), 250, 397, 399, 421, 426, 432, 441, 448, 450, 457, 468, 470, 472, 486, 488, 490, 496, 503, 511, 513
Shuttle Carrier Aircraft 474, 267
Shuttle Crew Operations Manual, 215
Shuttle Entry Data System (SEADS), 381, 386, 396, 405
Shuttle Infrared Leeside Temperature Sensing (SILTS), 386, 397, 398, 405
Shuttle Ionospheric Modification with Pulsed Local Exhaust (SIMPLEX), 524, 529, 532, 542
Shuttle Laser Altimeter, 498
Shuttle Pallet Satellite (SPAS), 160, 161, 163, 243, 362, 366, 401. *See also* ASTRO-Shuttle Pallet Satellite (ASTRO-SPAS)
Shuttle Pallet Satellite (SPAS) Payload Operations Control Center, 253
Shuttle Plume Impingement Experiment (SPIE), 437
Shuttle Plume Impingement Flight Experiment (SPIFEX), 472
Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN)
  201 mission instruments and experiments: Ultraviolet Coronal Spectrometer, 757–58, 759, 760, 987; Video Guidance Sensor, 760–61; White Light Coronograph, 757–58, 987
  201 satellites, 757–61, 987; 201-01 (Solar Physics), 161, 250, 365, 441, 758, 774, 987; 201-02 (Coordinated Observations-Ulysses), 162, 260, 368, 471, 758, 774, 987; 201-03 (Coordinated Observations-Ulysses), 163, 265, 491, 759, 775, 987; 201-04 (Calibration Flight-SOHO), 164, 272, 274, 373, 533, 759–60, 775, 987; 201-05 (Calibration Flight-SOHO), 164, 374, 545, 760–61, 775, 987
  204 (UV Astronomy-Stellar), 162, 261, 263, 368, 482, 484, 757, 761, 774
  207 (Inflatable Antenna Experiment), 163, 267, 370, 505
  accommodations for on Shuttle, 352
  attitude control system, 535, 757
  deployment of satellites, 757
  development of program, 756–57
  EVA to rescue, 359, 535
  Far Ultraviolet Imaging Spectrograph (FUVIS), 761
  free-flyer payload, 276
  OAST flyer, 163, 266, 370, 498
  objectives of, 757
  retrieval of, 757
Shuttle Small Payloads Project (SSPP), 223
Shuttle Solar Backscatter Ultraviolet (SSBUV) instrument, 239, 246, 382, 390, 409, 421, 465, 480, 498
Shuttle Student Involvement Project (SSIP)
  STS-29, 378
  STS-31, 389
  STS-41, 391
  STS-42, 417
Shuttle Training Aircraft, 487
Shuttle Upper Atmosphere Mass Spectrometer (SUMS), 397, 405
Shuttle Vibration Forces (SVF), 540
Shuttle-C, 77, 78, 79, 89, 101, 283
Shuttle/Spacelab Payload Mission Management and Integration budget category, 212, 329, 340
Sierra College, Rocklin, California, 473, 540
Simons, David, 822
Simplified Aid for EVA Rescue (SAFER), 272, 277, 357, 475, 504
  USA SAFER, 551
Simpson, John, 807
Single Stage Rocket Technology program (BMDO), 80

Single String Global Positioning System, 550
Single-element telescope, 949
Sisson, James, 203, 204
Sjogren, William, 927
Skylab, 247, 451
Slayton, Donald "Deke," 47–48
Sloeckler, George, 845
Slow Rotating Centrifuge Microscope (NIZEMI), 258
Slow-Turning Lateral Vessel (STLV) bioreactor, 414
Small Deep-Space Transponder, 858
Small Expendable Deployer System
  SEDS-1, 76, 77, 138
  SEDS-2, 77, 138
Small Explorer Data System, 598
Small Explorer missions (SMEX)
  budgets and funding for, 587
  management of, 55, 152, 592
  missions: FAST, 147, 579, 591, 601–3, 691, 771, 804–5; SAMPEX, 152, 579, 591, 598–99, 769, 790, 796–800, 809; SWAS, 148, 591, 610–12, 773, 790, 814–15; TRACE, 147, 579, 591, 608–10, 611, 691, 772, 790, 812–13; WIRE, 591–92
  objectives of, 577
  Pegasus for deployments, 55
  success of, 577
Small Mission Program Group, 713
Small Satellite Technology Initiative, 587
Small Self-Contained Payload (SSCP) program, 222–23. *See also* Get Away Special (GAS) program
Smith, David E., 952, 955
Smith, Peter, 961, 969
Smith, Steven L.
  STS-68, 368, 476
  STS-82, 358, 372, 519, 520, 632
Smithsonian Astrophysical Observatory (SAO)
  Advanced X-ray Astronomical Facility (AXAF), 652, 653
  balloon flights, 906, 907, 908, 912, 914, 917
  high-resolution imagers (HRIs), 616, 617, 817
  sounding rocket program, 883, 887, 888, 892
  Spitzer Space Telescope (Space Infrared Telescope Facility [SIRFT]), 659
  Ultraviolet Coronal Spectrometer, 757, 758
  Ultraviolet Coronograph Spectrometer (UVCS), 876
Smoot, George, 791
Smyth, William H., 936
Society of Japanese Aerospace Companies, Inc., 418, 451–52, 468, 474, 499
Soderblom, Lawrence A., 857
Sodium Sulfur Battery Experiment (LHP/NaSBA), 534
Soft Gamma Repeater (SGR), 650
Soft X-ray Spectrometer (SOXS), 861
Soft X-ray Telescope (SXT), 683–84, 879, 880
Sojourner microrover, 578, 724, 731, 732–33, 962
Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX), 579, 591, 598–99, 769, 790, 796–800, 809
Solar and Heliospheric Observatory (SOHO)
  characteristics, instruments, and experiments, 681, 875–78
  coordination of TRACE with, 609
  data and images from, 675, 681, 682
  deployment of, 46–47, 125, 681, 770, 875
  development and management of, 680–81, 875
  discoveries and scientific contributions from, 681–82, 878
  ISTP program, 672, 676, 680
  objective of, 579, 681, 770, 875
  problems experienced with, 682–83
  sounding rocket program and, 691
  SPARTAN satellites and, 759–60
Solar Array Module Plasma Interaction Experiment (SAMPIE), 465
Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET II), 669, 857
Solar Constant (SOLCON), 421, 441, 480, 528, 547
Solar Electric Ion Propulsion System, 856
Solar Energetic Particle Ionic Charge Analyzer (SEPICA), 607, 807, 808
Solar Extreme Ultraviolet Hitchhiker (SEH), 492
Solar Isotope Spectrometer (SIS), 607, 807
Solar Maximum Mission (SMM), 575, 608, 684
Solar physics missions, 578, 579, 768, 772
Solar Spectrum (SOLSPEC), 421, 441, 480
Solar system exploration, 577, 589
Solar System Exploration Committee, 739, 740
Solar System Exploration Division (Office of Space Science), 583, 584, 585, 589, 713, 714
Solar System Exploration Division (Office of Space Science and Applications), 581, 582
Solar Ultraviolet Experiment (SUVE), 440
Solar Ultraviolet Measurements of Emitted Radiation (SUMER), 876
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM), 421, 441, 480
Solar Wind and Suprathermal Ion Composition Experiment (SMS), 868
Solar Wind Anisotropies (SWAN), 876
Solar Wind Experiment (SWE), 867
Solar Wind Ion Mass Spectrometer (SWIMS), 607, 807
Solar Wind Ionic Composition Spectrometer (SWICS), 607, 662, 807, 845, 868
Solar Wind Plasma (SWOOPS) Experiment, 844
Solar X-ray Photometer (SXP), 810
Solar X-rays and Cosmic Gamma Ray Bursts, 847
Solar-A/Yohkoh, 683–85, 768, 879–81
Solid Propulsion Integrity Program (SPIP), 27
Solid rocket boosters
  budgets and funding for, 92, 93, 108, 112
  characteristics of, 66, 68, 166, 215, 216
  management of, 65
Solid rocket motor, 34, 89, 93, 109, 113, 491
Solid State Microaccelerometer Experiment, 406
Solid Surface Combustion Experiment (SSCE), 390, 410, 432, 440, 472, 483, 529, 542
Solid-state Imaging Spectrometers (SISs), 665, 849, 850, 851
Solid-state Imaging (SSI) camera, 934

Solid-state recorder, 632
Solovyev, Anatoly, 303, 487
Sondre Stronfjord, Greenland, 911, 912
Sounding rocket program, 690–92, 756, 882–905
South America, 388, 688
Southwest Research Institute
  Cassini Plasma Spectrometer (CAPS), 973
  Ion and Neutral Mass Spectrometer (INMS), 974
  Plasma Experiment for Planetary Exploration (PEPE), 858
  sounding rocket program, 895, 898, 901, 902, 905
Southwest Ultraviolet Imaging System (SWUIS), 529
Southwood, David J., 975
Soviet Union, 291, 298–99, 300, 672, 677
Soyuz vehicle
  Apollo-Soyuz Test Project, 264
  crew transfer to *Mir*, 262, 300, 303, 555
  crew transfer to Salyut space stations, 298–99
  crew transfer vehicle for Space Station, 280, 293, 294, 296, 305, 557
Space Acceleration Measurement System (SAMS), 245, 410, 417, 430, 436, 440, 481, 483, 500, 518
Space Access and Technology, Office of (Code X)
  budgets and funding for, 13, 33, 35, 89, 97, 100
  disbanding of, 32
  New Millennium Program, 667
  organization of, 29
  responsibilities of, 13, 30
  Space Station funding, 214
Space Access and Technology program, 172, 214
Space Aerospace, Ltd. Canada, 434
Space Astronomy and Astrophysics joint working group, 677
Space Astrophysics Group, University of California, Berkeley, 764
Space Automation and Robotics Center, Ann Arbor, Michigan, 472
Space Classroom Program, "Assignment—The Stars," 397
Space Communications, Office of, 14, 32, 193
Space Development and Commercial Research Division, 212
Space Development office (Office of Space Flight), 31, 32, 193
Space Experiment Module (SEM) Carrier System, 223
Space Experiment Module (SEM) program, 223, 352, 515, 544, 548, 551
Space Exploration, Office of, 10
Space Flight, Office of (Code M)
  appropriations and functional areas, 9, 12, 15
  code letter designations, 192
  organization and management of, 24–32, 193, 203–4, 206, 209–10, 282
  responsibilities of, 23, 26, 30, 193, 205, 208, 210, 282
Space Flight/Space Station Integration Office, 203
Space Flyer Unit, 266
Space Industries, Inc., 423
Space Infrared Telescope Facility (SIRFT), 589, 657–60, 782
Space Infrared Telescope Facility (SIRFT) Science Working Group, 659
Space Infrared Telescope Facility (SIRFT) Task Group, 659
Space Integrated Global Positioning System,/Inertial Navigation System (SIGI), 551
Space Launch Initiative, 84, 88
Space Life Sciences Strategic Plan (1992), 210
Space Operations office (Office of Space Flight), 31, 32, 193
Space Operations Utilization office (Office of Space Flight), 32
Space Physics Division (Office of Space Science), 583, 584, 588
Space Physics Division (Office of Space Science and Applications), 581
Space Physics Laboratory, Lockheed Martin Advances Technology Center, 873, 874
Space physics missions, 578, 579–80, 588, 589, 767, 769, 770, 771, 772
Space Processing division (Office of Space Access and Technology), 29
Space Program, Advisory Committee on the Future of the U.S., 204–5, 287
Space Radar Laboratory (SRL)
  SRL-1, 256, 257, 260, 367, 468
  SRL-2, 162, 260, 368, 477
Space Radiation Laboratory, California Institute of Technology, 806
Space Radiation program, 619
Space Research Institute, 968
Space Science and Applications, Office of (Code E/Code S)
  budgets and funding for, 9, 35, 90, 95
  "faster, better, cheaper" concept, 577
  Hubble Space Telescope investigation, 622–23
  Launch Vehicle Office, 27
  Life Sciences Division, 210–11, 385
  Microgravity Science and Applications Division, 210, 211
  organization and management of, 580–82
  PCG, 378
  Pool Boiling Experiment, 452, 462
  responsibilities of, 9, 27, 29, 283, 580–82
  SHARE, 377
  space science missions sponsored by, 575
  STL experiment, 421
Space Science Board, National Academy of Sciences, 740
Space Science Committee, European Science Foundation, 740
Space Science Development, Office of, 12
Space Science Enterprise, 583
Space science missions
  budgets and funding for, 585–88, 776–89; authorized budget, 587, 776; programmed budget, 587, 777
  Centers of Excellence, 584
  discipline areas, 574, 575, 577–80, 588–89
  "faster, better, cheaper" concept, 577, 582,

587–88, 772
  international scope of, 574
  knowledge gained through, 574
  last decade review, 575
  list of, 767–73
  management of, 574, 580–85
  method of deployment, 573–74
  number launched, 573, 576
  overview of, 576–80
  PI-led missions, 579, 580, 590
  size of missions, 576–77
  Space Shuttle missions, 774–75
  themes of, 583, 584
  Web sites for, 574
Space Science, Office of (OSS)
  CGRO reentry, 651
  Deep Space 1, 668
  Mars Climate Orbiter Mission Failure Mishap Investigation Board, 738
  missions sponsored by, 575
  New Millennium Program, 667
  organization and management of, 582, 583–85, 586
  responsibilities of, 582
  Strategic Plan, 583, 584
Space Science Project Web sites, xxiii
Space Sciences Department, Aerospace Corporation, 873
Space Sciences Laboratory, University of California, Berkeley, 793, 868, 872
Space Shuttle
  abort modes, 236–38
  activities and events of typical mission, 217
  beginning of program, 190
  budgets and funding for, 30, 33–36, 89, 92–94; assured shuttle availability, 93, 109; flight hardware, 111; flight operations, 110–11; flight operations upgrades, 92, 106; launch and landing operations, 93, 113–14; launch and mission support, 92, 106–7, 110; launch services mission support, 94, 117; main engine, 93, 106–7, 112; Orbiter Operational Capability, 104–5; Production and Operational Capability, 15, 33, 34, 35–36, 89, 90, 103, 110; propulsion systems, 92–93, 108, 109, 112–13; Safety and Performance Upgrades, 33, 35, 89, 92, 94, 96, 103, 109; Space Transportation Operations, 110
  Certification of Flight Readiness, 194
  characteristics of, 65–69
  components of, 215–16
  crew: age of, 516; assignments and duties, 233–34; number of, 217; selection of, 232, 540; services provided by, 234–36
  external tank, 215, 216; budgets and funding for, 92, 93, 108, 113; characteristics of, 65–66, 165; super lightweight external tank (SLWT), 276
  fleet of, 20
  Flight Readiness Review, 194
  functions and missions of, 19, 190–91, 216–17
  launch and landing operations, 69, 217; budgets and funding for, 93, 113–14; contingency landing sites, 217; Edwards Air Force Base, 69, 217, 237, 502; Kennedy Space Center, 69, 194, 217, 237, 244, 250–51, 260, 385, 392, 454, 512, 514; night landing, 454, 502
  launch vehicle function of, 19, 20–21, 22, 23, 49, 64, 190
  low-Earth orbit of, 41
  main engines (SSME), 215, 216; Block I, 67, 264, 267; Block II, 545; Block IIA, 67; budgets and funding for, 93, 106–7, 112; characteristics of, 66–67, 69, 166, 350; scrub or abort modes, 237, 238
  management of program for, 23–32, 192, 193–95, 205, 582
  Mission Management Team, 194
  NASA's responsibility to upgrade, 22
  orbiter, 215, 216; budgets and funding for, 92, 104–5, 111; characteristics of, 217–19, 349–50; extended duration orbiter, 92, 105, 219, 247, 255, 354–55, 414, 470, 486, 495, 511, 522, 527, 540; glass cockpit, 221; management of, 65; modifications and upgrades to, 219–21, 258, 425; Orbiter Docking System, 220, 229–30
  Orbiter Maintenance Down Period (OMDP), 219, 220–21, 249, 519, 536
  private sector operation and management of, 23
  processing work, contract for, 64
  Reaction Control System, 472
  reliance on, end to, 78, 183
  solid rocket boosters, 215, 216; budgets and funding for, 92, 93, 108, 112; characteristics of, 66, 68, 166; management of, 65
  solid rocket motor, 34, 89, 93, 109, 113, 491
Space Shuttle missions. *See also STS entries*
  African-American crew: first to walk in space, 261; first woman, 248
  altitude numbers in mission descriptions, 238
  Challenger explosion and, 20
  chronologies, xxiii, 238
  "dog crew," 265
  female astronauts, 248, 255, 258
  female Shuttle pilot, 261
  funding for, 6, 15
  Japanese citizen to walk in space, 499
  Kennedy Space Center employee as astronaut candidate, 540
  length of, 247, 255, 258, 262, 265, 268, 269, 469
  length of time in space for astronauts, 268, 272
  list of, 159–64, 360–75
  married couple as crew, 248
  number of flights, 21, 64, 190, 238, 266
  oldest human to fly in space, 516
  orbiter-to-orbiter crew conversation, 449
  payload mission management and integration, 780
  payloads: accommodations for, 221–32, 351–52; attached space science missions, 750. *See also specific missions*; commercial, 49; criteria for, 22, 64; examples of, 64; NAVSTAR

  - GPS satellites, 50; removal of DOD payloads, 61, 249, 439; satellites, 69, 750. *See also specific satellites*; small payloads, 221, 222–23; types of, 221–22
  - President at launch, 548
  - press and media kits, xxi, 238
  - reflight of mission, 164, 270, 355, 372, 525, 527
  - safety emphasis following *Challenger*, 70, 190
  - space science missions and experiments, 573, 575, 774–75
  - success rate for launches, 21, 190
  - successful missions, 190, 238
- Space Shuttle Operations funding, 33
- Space Shuttle Program Director (Office of Space Flight), 193
- Space Shuttle Program Office, 196
- Space Shuttle Projects Office, Marshall Space Flight Center, 194, 195
- Space Shuttle/Spacelab Mission Management and Integration program, Office of Life and Microgravity Sciences and Applications, 196
- Space Station, 566. *See also* International Space Station (ISS); *Mir* Space Station; Space Station *Freedom*; United States-Russian Cooperative Program
  - assembly of, 3, 234
  - assembly techniques, practice of, 247, 356, 424, 484
  - budgets and funding for: *Alpha*, 191, 208, 296; *Freedom*, 191, 208, 281–84, 287–88, 290, 293–96, 552, 565, 566; funding history, 333–43; Human Space Flight (HSF) appropriations, 35, 213–15, 324–26; ISS, 305, 312, 313–14, 568, 570; Programmed Budget, 327–30; Science, Aeronautics, and Technology (SAT) appropriations, 213–15; Space Transportation Capability Development appropriations, 34; Spaceflight, Control, and Data Communications (SFC&DC) appropriations, 6, 15
  - chronology of, 564–70
  - development of, 190, 199, 277–78
  - management of, 192, 197–210
  - resupply missions to, 85
  - Space Shuttle missions to, 164
- Space Station *Alpha*, 191, 208, 277, 296, 566
- Space Station Control Board, 306, 569
- Space Station *Freedom*
  - assembly of, 284, 290, 291, 292
  - assembly techniques, practice of, 247, 356, 424
  - Assisted Crew Return Vehicle, 290
  - budgets and funding for, 191, 208, 213, 281–84, 287–88, 290, 293–96, 552, 565, 566
  - characteristics of, 553–54
  - chronology of, 564–67
  - components, systems, and modules, 281, 282–91; Crew and Equipment Translation Aids (CETA), 242, 356, 400; ESA attached pressurized module, 284, 285, 286; Exposed Facility, 284, 289; Japanese Experiment Module, 284, 285, 287; Space Station Remote Manipulator System (SSRMS), 285, 289; Special Purpose Dexterous Manipulator (SPDM), 284–85, 289; U.S. habitation module, 284, 285, 286, 288; U.S. laboratory module, 284, 285, 288
  - Configuration Budget Review Team, 283, 564
  - contractor-led joint vehicle integration team, 206, 208
  - contractors for, 281, 552, 564, 566
  - crew, number of, 288, 554
  - development of, 190, 191, 280–81
  - External Maintenance Solutions Team, 286, 564
  - External Maintenance Task Team (EMTT), 286, 564
  - flight telerobotic servicer (FTS), 285, 288
  - Health Maintenance Facility, 430
  - heat transport systems, 377
  - life sciences experiments, 210, 293
  - management of program for, 25, 26, 28, 30, 31, 193, 197–208, 582
  - man-tended capability, 290, 292
  - metal experiments to support, 407
  - *Mir* program and, 291–93, 294
  - mission, goals, and objectives, 290
  - naming of, 191, 280
  - National Launch System and, 79
  - orbit of, 291
  - permanently manned capability, 290, 291, 292
  - redesign of, 191, 208, 213, 283–84, 286–88, 293–97, 565–66
  - STLV bioreactor, 414
  - termination of, 304, 567
  - U.S.-Russian Cooperative Program and, 293, 567
  - water electrolysis, 492
- Space Station Freedom Program Office, 203, 204, 206, 207, 252, 290
- Space Station Freedom Strategic Plan, 206, 207
- Space Station Freedom Systems Integration Office, Johnson Space Center, 204
- Space Station Heat Pipe Advanced Radiator Element (SHARE), 377, 409
- Space Station, Office of (Code S)
  - administrators of, 203
  - appropriations and functional areas, 9
  - code letter designations, 192
  - consolidation of, 24–25, 203, 282
  - organization of, 197, 198
- Space Station Program Office (Office of Space Flight), 193, 198, 208
- Space Station Remote Manipulator System (SSRMS), 279, 285, 289
- Space Station Transition Team, 296
- Space Stations Project Offices, 198
- Space Systems Development, Office of (Code D)
  - "Access to Space" study, 22, 80, 172
  - code letter designations, 193
  - Flight Demonstration Program, 76
  - management of, 26
  - National Launch System management by, 79
  - organization of, 25–26, 29, 205
  - responsibilities of, 26, 28, 193, 205, 206, 208,

210
Space Systems division (Office of Space Access and Technology), 29
Space Systems Inc. (SSI), 47–48
Space Technology program, 27
Space Telescope Imaging Spectrograph (STIS), 358, 519, 630, 632, 829–30
Space Telescope Operations Control Center, Goddard Space Flight Center, 459, 631
Space Telescope Science Institute (STScI), 621, 626
  Faint Object Camera (FOC), 825
  Multimission Archive, 687, 689
  Web site for, xxiii
Space Test Payload-1 (STP-1), 402
Space Test Program
  Army, 421
  DOD, 381, 761
Space Tissue Loss (STL), 421, 439, 443, 468, 481, 490, 515
Space Tracking and Data Systems, Office of, 10, 15
Space Transportation Architecture Study, 183
Space Transportation Capability Development appropriations, 9, 12, 33, 34, 89, 90, 96, 212
Space Transportation division (Office of Aeronautics and Space Transportation Technology), 32
Space Transportation division (Office of Space Access and Technology), 29
Space Transportation Main Engine (STME), 78, 79
Space Transportation Operations budgets and funding, 15, 34, 36, 93, 110
Space Transportation System, 20, 34
Space Transportation Technology division (Office of Aeronautics and Space Transportation Technology), 32
Space Vision System, 279
Spaceborne Imaging Radar-C (SIR-C), 256, 257, 477
Spacecraft Bubble Data Recorder (BDR), 684, 685
Spacecraft Kinetic Infrared Test (SKIRT), 465
Spaceflight, Control, and Data Communications (SFC&DC) appropriations, 6, 33, 34–36, 89, 90, 92–94
SPACEHAB
  access to, 252
  characteristics of, 252
  configuration of modules, 228–30, 231
  development of program, 227–28
  Shuttle missions, 355; STS-57, 161, 252, 355, 366, 450; STS-60, 255, 355, 367, 460–61; STS-63, 162, 261, 355, 368, 482–83; STS-76, 355, 370, 503; STS-77, 164, 267, 355, 505; STS-79, 268, 355, 371, 513; STS-81, 269, 355, 371, 517; STS-84, 355, 372, 523–24; STS-86, 272, 273, 355, 373, 531, 536; STS-89, 274, 355; STS-91, 355, 374, 541; STS-95, 164, 276, 355, 374, 546
  as Shuttle payload, 352
  Space Research Laboratory, 227–30, 252
  space science missions, 750
  support for Shuttle-*Mir* activities, 228, 267, 268, 272, 273, 274, 275, 531, 536, 541
  workspace provided by, 227–28, 231, 352
SPACEHAB, Inc., 227–28
Spacelab. *See also* Astro-1; Astro-2
  animal enclosure modules, 231–32
  budgets and funding for, 34, 35, 212, 327, 332
  characteristics of, 353
  command and data management system (CDMS), 227
  components of, 224–26
  data processing assembly (DPS), 227
  design and development of, 224
  experiments on, control of, 225
  igloo, 226, 242, 262, 354, 362, 365, 420, 441
  instrument pointing system, 227
  international cooperative focus of, 575
  investigations carried by, 224, 227
  last decade review, 190
  Life and Microgravity Spacelab (LMS), 163, 268, 354, 371, 509–11
  life sciences missions, 161, 354, 575; SLS-1, 243–44, 354, 362, 404; SLS-2, 255, 354, 366, 455–57
  management of, 26, 193, 196, 205, 582
  microgravity research, 495
  Mir research and payloads, 191, 196, 229, 354, 488
  Mission Operations Control, Huntsville, Alabama, 258, 270
  missions flown with, 227, 354–55
  Neurolab mission, 164, 274–75, 355, 374, 538–39
  number of missions, 191
  orbiter modifications to accommodate, 219
  pallets, 226, 242, 262, 264, 351, 354, 362, 365, 420, 441
  payload mission management and integration, 780
  Payload Operations Control Center, 196
  research missions and payloads, 191
  as Shuttle payload, 221, 224–27, 351, 352
  space science missions, 575, 750
  Spacelab D-1, 445, 448
  Spacelab D-2, 161, 251, 354, 366, 445–48
  Spacelab-J, 161, 248, 354, 364, 429–32
  ultraviolet telescopes mounted on, 396
  workspace provided by, 225, 352
Spain
  abort landing facility, 237
  Deep Space Network (DSN) station, 666, 701
  ESA membership, 279
  Laboratory for Space Astrophysics and Theoretical Physics, 687
  Minisat 01, 55
  payloads launched for, 21
  Pegasus ELVs, 55
  Villafranca Satellite Tracking Station, 688, 689
Spar Astro, 552
Spearing, Robert, 32
Special Purpose Dexterous Manipulator (SPDM)
  Freedom, 284–85, 289
  ISS, 279, 306, 316, 319

Spectrometer Measurement of the Upper Atmosphere in the UV Range, 473
Spectrum Astro, Inc., 668, 856
Spektr module, 272, 300, 303, 487, 489, 544, 568
Spiral galaxy M100, 623, 624
Spiral galaxy NGC 4603, 641, 642
Spitzer, Lyman, 620
Spitzer Space Telescope (Space Infrared Telescope Facility [SIRFT]), 589, 657–60, 782
Springer, Robert C.
  STS-29, 360, 376
  STS-38, 361, 392
Sromovsky, Larry, 933
St. Vincent Elementary School Salt Lake City, Utah, 543
Stanford, I. Duke, 24
Stanford University
  Energetic Gamma Ray Experiment Telescope (EGRET), 646, 835
  Michelson Doppler Imager/Solar Oscillations Investigation (MDI/SOI), 878
  Radio Science Experiments, 953, 956
  Radio Science: Propagation, 936
  sounding rocket program, 887, 897
Star Tracker Cameras, 950
Stardust, 715, 938
Stars
  ASCA discoveries, 852
  Astro-2, 984–86
  dense stellar environments, 635–36, 639
  galaxy collisions and, 638, 641
  life cycle of, 634
  magnetic star SGR1900+14, 662
  Supernova 1006, 852, 985
  Supernova 1987A, 634, 636, 638, 836, 980
  Type Ia supernovae, 643–44
  U Geminorum, 985
  x-ray radiation from, 249
State University of New York, 936
State University of New York at Stony Brook, 377
Station Redesign Team, 294, 565
Stecher, Theodore P., 982
Stein, Martin, 29
Stellar Oscillation Photometer, 966
Stennis Space Center
  aerospike engines, 184
  budgets and funding, 34
  Center of Excellence designation, 11
  engine oxidizer duct testing, 494
  management of, 28, 31
  mission area, 11
  responsibilities of, 194
  X-33 testing, 182
Stephenson, Arthur G., 738
Stereo-spectral Imaging System, 964
Still, Susan L.
  STS-83, 372, 521
  STS-94, 372, 525
Stone, Edward, 797, 798, 806, 935
Strategic Defense Initiative Organization (SDIAO), 720. *See also* Ballistic Missile Defense Organization (BMDO)
  Infrared Background Signature Survey experiment, 160
  Space Shuttle experiments, 243
Strategic Defense Initiative (SDI), 77–78
Strategic Enterprises, 30
Strategic Planning office (Office of Space Flight), 32
"Strategy for Space Astronomy and Astrophysics for the 1980s" (National Research Council), 658
Stratospheric Observation for Infrared Astronomy, 783
Strekalov, Gennadiy, 487
Structural Dynamics Model Validation, 551
Structure and Evolution of the Universe Division (Office of Space Science), 584, 585
STS-1, 398
STS-2, 398
STS-3, 398
STS-4, 219, 222, 398
STS-5, 219, 398
STS-9, 191, 219
STS-28, 159, 239, 380–81
STS-29, 159, 168, 238, 376–78
STS-30, 159, 239, 379
  IUS launch, 72, 75
  Magellan deployment, 72, 75, 159, 239, 360, 379, 693–94, 767, 927
STS-31, 159, 241, 388–89
STS-32, 159, 240, 385–86, 397, 405
STS-33, 159, 168, 239, 384
STS-34, 159, 168, 239, 382–83
  Galileo deployment, 159, 239, 360, 382, 383, 703, 767, 930, 932
STS-35, 159, 242, 392, 394–98, 405, 756, 774, 981
STS-36, 159, 240, 387, 395
STS-37, 159, 242, 356, 399–400, 645, 833
STS-38, 159, 242, 392–93
STS-39, 160, 243, 401–2, 762
STS-40, 160, 219, 243–44, 397, 403–8
STS-41, 159, 168, 241–42, 390–91, 843
STS-41-C, 240, 361
STS-41-D, 237, 238
STS-42, 160, 220, 244–46, 415–19
STS-43, 160, 168, 244, 409–10
STS-44, 160, 168, 244, 413–14, 522
STS-45, 160, 246, 420–21
STS-46, 160, 247–48, 427–28
  EURECA, 247, 252, 253, 427, 428
  TSS deployment, 74, 427, 428
STS-47, 161, 248, 429–34
STS-48, 160, 244, 411–12
STS-49, 64, 160, 218, 246–47, 356, 422–24
STS-50, 160, 247, 425–26
STS-51, 161, 252–54, 357, 449, 453–55, 763, 774, 775
STS-51-B, 449
STS-51-D, 449
STS-51-F, 238
STS-51-L, 190. *See also Challenger*
STS-51-L Data and Design Analysis Task Force, 190
STS-52, 161, 249, 435–37
STS-53, 161, 249, 438–40

STS-54, 161, 168, 249, 356, 440, 755, 756, 774
STS-55, 161, 238, 250–51, 444–48
STS-56, 161, 250, 441–43, 758, 774
STS-57, 161, 228, 252, 253, 355, 356, 449–52, 474
STS-58, 161, 255, 455–57
STS-59, 162, 256–57, 260
STS-60, 162, 255–56, 355, 460–63
STS-61, 161, 236, 255, 357, 458–59, 623, 628–30, 630, 774
STS-61-B, 248
STS-61-C, 223, 494
STS-62, 162, 256, 464–66
STS-63, 162, 261–62, 355, 357, 482–84, 774
  Shuttle-*Mir* program, 300, 304, 555, 567
  SPARTAN 204 mission, 761
STS-64, 162, 260, 357, 471–75, 758, 774
STS-65, 162, 258–59, 469–70
STS-66, 162, 260–61, 479–81
STS-67, 162, 262–63, 485–86, 754, 775, 981
STS-68, 162, 260, 476–78
STS-69, 163, 265, 357, 491–93, 759, 775
STS-70, 162, 168, 264, 489–90, 491
STS-71, 162, 263–64, 487–88, 491
  Shuttle-*Mir* program, 300, 301, 302, 555
STS-72, 163, 266, 358, 498–99
STS-73, 163, 265, 494–95
STS-74, 266, 496–97
  Shuttle-*Mir* program, 300–301, 496, 497, 555
STS-75, 75, 163, 266, 500–501
STS-76, 163, 266–67, 355, 358, 502–4
  Shuttle-*Mir* program, 502, 504, 555
STS-77, 163, 267, 355, 505–7
STS-78, 163, 268, 508–11
STS-79, 163, 268, 355, 512–13, 514, 555
STS-80, 163, 269, 514–16
STS-81, 163, 269, 355, 517–18, 555
STS-82, 163, 269, 358, 519–20, 630–33, 775
STS-83, 163, 270, 521–22, 525
STS-84, 164, 270, 355, 523–24, 555
STS-85, 164, 270–71, 528–30
STS-86, 164, 272, 273, 355, 531–32, 555
STS-87, 164, 272, 274, 276, 359, 533–35, 759–60, 775
STS-88, 64, 164, 277, 316–17, 319, 359, 549–51
  ISS assembly mission, 277, 313, 315–17, 318, 319, 359, 374, 562–63
STS-89, 164, 274, 355, 536–37, 555
STS-90, 164, 227, 274–75, 538–40
STS-91, 164, 275–76, 355, 541–44, 555
STS-94, 164, 270, 522, 525–27
STS-95, 164, 276, 355, 545–48, 633, 760–61, 775
Student Experiment on ASTRO-SPAS (SEAS), 766
Student Explorer Demonstration Initiative (STEDI) program, 592–93
  budgets and funding for, 592
  CATSAT, 592, 593
  SNOE, 147, 592, 593, 605–6, 609, 772, 790, 810–11
  TERRIERS, 592, 593
  ultralite ELV launch services, 592–93
Student Nitric Oxide Explorer (SNOE)
  deployment of, 147, 593, 605–6, 609, 772, 790, 810–11
  funding for, 592
  objective of, 772
Student Shuttle Flight Program, 231
Student Undergraduate Research Fellowship Satellite, 139
Students for the Exploration and Development of Space (SEDSAT), 141, 667, 669–71, 773, 859
Sturckow, Frederick R., 317, 374, 549
Submillimeter Wave Astronomy Satellite (SWAS), 148, 591, 610–12, 773, 790, 814–15
Suborbital program
  balloon flights, 693, 694, 906–25
  objectives of, 690
  sounding rocket program, 690–92, 882–905
  Ultra-long Duration Balloon (ULDB) project, 693
Suborbital Research program, 588, 783
Sullivan, Kathryn D.
  STS-31, 361, 388
  STS-45, 364, 420
Summa Technology, 84
Sun
  ATLAS-3, 260–61, 480
  atmosphere of, study of, 265, 276
  energy output: data collection on, 260–61, 480; investigations of, 575
  Galileo, 704
  high-frequency solar output, 452
  SOHO, 46–47, 125, 579, 609, 680–83, 691, 770
  Spacelab mission research, 227
  TRACE, 147, 579, 591, 608–10, 611, 772, 790, 812–13
  Ulysses and, 241, 265, 661–62, 663, 768, 842
  Yohkoh/Solar-A, 683–85, 768, 879–81
Sun-Earth Connection Division (Office of Space Science), 584, 585
Sun-Earth-Heliosphere Connection theme, 583, 608, 679
Superfluid Helium On-Orbit Transfer (SHOOT), 450
Supernova 1006, 852, 985
Supernova 1987A, 634, 636, 638, 836, 980
Supernovae Type Ia, 643–44
Suprathermal Ion Composition Spectrometer (STICS), 863, 868
Surface Effects Sample Monitor (SESAM), 269, 271, 764, 765, 988
Surface-science Package (SSP), 979
Svalbard, Norway, 904
Sverdrup Corporation, 171, 175, 178
Swank, Jean, 802
Sweden
  ESA membership, 279
  International Solar-Terrestrial Physics (ISTP) program, 672
  Swedish Space Corporation, 418, 433, 477
  TRACE, 608, 812
Switzerland, 246, 279, 672
SYNCOM satellite, 159, 240, 361, 385
Synthetic aperture radar (SAR), 694–95, 697, 928

Systems Integration Office, Johnson Space Center, 204

T

Tam, Dan, 210
Tananbaum, Harvey, 652
Tank Pressure Control Equipment (TPCE), 409
  TPCE/RFL, 506
  TPCE/TP (Thermal Phenomena), 437
Tanner, E. Ray, 203
Tanner, Joseph R.
  STS-66, 368, 479
  STS-82, 358, 372, 519, 520, 632
Task Force Red Team, 304
Tateyama, N., 474
Taurus ELVs
  characteristics of, 20, 59, 60, 153
  development of, 59
  launches with, 21, 38, 39, 40, 59, 61, 118, 154
  payloads, 61
  success rate for launches, 38, 118
Teachers and Students Investigating Plants in Space (TSIPS), 534
Technical University of Clausthal, Germany, 537
Technology Applications and Science (TAS) experiments, 271, 528
Technology demonstrator missions, 769, 773
Technology Experiments Facility, 280
Technology Experiments for Advancing Missions in Space (TEAMS), 267, 506
Teegarden, B. J., 869
Teledyne Brown, 552
Telespazio, 854
TENMA, 850
Terra Scout, 413
Test Director, NASA, 237
Tethered Satellite System (TSS)
  deployment of, 247, 248, 427, 428
  experiments with, 74–77
  funding for, 34, 91, 99
  purpose of, 74
  Space Shuttle missions, 163, 266, 364, 370, 500, 501
Thagard, Norman E.
  aboard *Mir*, 264, 267, 300, 488, 555
  IML-1, 245
  STS-30, 360, 379
  STS-42, 245, 363, 415
  STS-71, 264, 487
Thebe, 711
Theory of Relativity, 803, 848, 851
Thermal and evolved gas analyzer, 970
Thermal Emission Spectrometer (TES), 726, 952, 955
Thermal Energy Management Processes (TEMP), 377, 427
Thermal Energy Storage (TES), 465, 492
Thermal Ion Dynamics Experiment (TIDE)/Plasma Source Instrument (PSI), 680, 873
Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED), 783
Thiokol Corporation
  Athena ELVs, 41, 120, 121
  Atlas ELVs, 127, 134
  Conestoga ELVs, 48, 135
  Delta ELVs, 50, 51, 142, 143, 144
  Space Shuttle engines, 65
  Taurus ELVs, 153
Thirsk, Robert Brent, 371, 508
Thomas, Andrew S.W.
  aboard *Mir*, 274, 275, 536, 555
  STS-77, 370, 505
  STS-89, 274, 373, 536
  STS-91, 275, 374
Thomas, Donald A.
  STS-65, 367, 469
  STS-70, 369, 489
  STS-83, 372, 521
  STS-94, 372, 525
Thomas Hancock, 408
Thompson, Rodger I., 831
Thornton, Kathryn C.
  STS-33, 360, 384
  STS-49, 356, 364, 422, 424
  STS-61, 357, 367, 458, 459, 628
  STS-73, 369, 494
Thorson, Richard A., 204
3D PLASMA, 867, 868–69
Thuot, Pierre J.
  STS-36, 361, 387
  STS-49, 356, 364, 422
  STS-62, 367, 464
Time-of-Flight Energy Angle Mass Spectrograph (TEAMS), 805
Titan. *See also* Huygens science probe
  discovery of, 740
  Huygens science probe, 743
  missions to explore, 575, 740
  objectives of Cassini-Huygens, 971
Titan ELVs
  characteristics of, 62, 158
  development of, 61–62
  inertial upper stage (IUS), 72, 168
  launches with, 21, 38–40, 61, 62–63, 118, 155–57, 424
  management of, 29
  success rate for launches, 38, 118
  Titan II, 20, 29, 62, 155–57, 158
  Titan IIG, 721, 948
  Titan III, 61, 62, 70, 155, 952
  Titan IV, 20, 61, 62
  Titan IVA, 61, 155–57
  Titan IVB, 62, 156, 157, 971
  Titan IV/Centaur, 29, 38, 72, 167
  Titan IV-IUS, 72, 168
Title, Alan, 812
Titov, Vladimir G.
  STS-63, 261, 368, 482
  STS-86, 272, 373, 531
Tokyo, Japan, 312, 569
Tokyo Institute of Technology, Earth and Planetary Sciences, 865
Tomasita Young Astronauts Club, Albuquerque, New Mexico, 544
Tomasko, Martin G., 978

Tomographic Experiment using Radiative Recombinative Ionospheric EUV and Radio Sources (TERRIERS), 592, 593
Toroidal Imaging Mass Angle Spectrograph (TIMAS), 873
Torsti, Jarmo, 877
Total Ozone Mapping Spectrometer Earth Probe (TOMS-EP), 147
Toughened Uni-Piece Fibrous Insulation (TUFI), 257
Toulouse, France, 309, 568
Tracking and Data Relay Satellites (TDRS)
  communication access to, 272
  communication through TDRS: for Compton Gamma Ray Observatory (CGRO), 647; for Hubble Space Telescope, 631; for ISS and Shuttle, 309
  configuration of, 250
  deployment of: TDRS-4, 159, 238, 360, 376; TDRS-5, 160, 244, 363, 409; TDRS-6, 161, 249, 365, 440; TDRS-7, 162, 264, 369, 490
  development of, 238
  IUS launch, 168, 244
  management of, 194
  RWTE data, 600
  testing of, 621
Trafton, Wilbur C., 28, 30, 32, 208, 209, 210
Transient Gamma Ray Spectrometer (TGRS), 869
Transition Region and Coronal Explorer (TRACE), 147, 579, 591, 608–10, 611, 691, 772, 790, 812–13
Transportable orbital tracking station (TOTS), Alaska, 603
Transportation, Department of, 48
Transportation Division (Office of Advanced Concepts and Technology), 27–28
Transportation Technology Support, 103
Trapped Ions in Space (TRIS) experiment, 503
Trauger, John T., 829
Trinh, Eugene H., 364, 425
Triton, 748, 749
Trombka, Jacob I., 941
Truly, Richard, 24, 25, 27, 203, 205, 282, 291, 565, 576, 577
Trümper, Joachim, 817
Truth, Sojourner, 731
TRW, Inc.
  Advanced X-ray Astronomical Facility (AXAF), 653, 654–55, 838
  Compton Gamma Ray Observatory (CGRO), 645, 833
  High Energy Astronomy Observatory (HEAO), 653
  National Launch System, 79
  sounding rocket program, 884
  Space & Electronics Group, 833
  Space Station contract, 552
TRW Defense and Space Systems Group, 433
Tryggvason, Bjarni V., 373, 528
Tsibliev, Vasily, 303
Tsou, Peter, 478
Tsuruda, Koichiro, 864
Tuamoto Archipelago, 428
Turbulent Gas-Jet Diffusion Flames (TGDF), 534
Turin, Italy, 310–11
Tyler, G. Leonard, 953, 956
Tyngsboro, Massachusetts, 439
Type Ia supernovae, 643–44

U

U Geminorum, 985
Uhran, Mark, 212
Ukraine, 272, 533, 534
Ulrich, Peter, 585
Ultra Low Energy Isotope Spectrometer (ULEIS), 607, 807
Ultralite ELV launch services, 37, 592
Ultra-long Duration Balloon (ULDB), 693
Ultraviolet and Visible Astrophysics Branch, 584
Ultraviolet CCD cameras, 861
Ultraviolet Coronal Spectrometer, 757–58, 759, 760, 987
Ultraviolet Coronograph Spectrometer (UVCS), 876
Ultraviolet Imager (UVI), 679, 680, 873
Ultraviolet Imaging Spectrograph (UVIS), 977
Ultraviolet Imaging Telescope (UIT)
  Astro-1, 396, 750–51, 752, 982
  Astro-2, 485, 486, 754, 982
Ultraviolet Plume Imager (UVPI), 410, 414, 423, 426, 428, 432
Ultraviolet Spectrograph Telescope for Astronomical Research (UVSTAR), 492
Ultraviolet Spectrometer (UVS), 810, 934
Ultraviolet Spectrophotometer, 964
Ultraviolet/Visible CCD Camera (UV/Vis), 949
Ulysses
  budgets and funding for, 660
  characteristics, instruments, and experiments, 660, 663–64, 843–48, 973; Coronal-Sounding Experiment (SCE), 847; Cosmic Ray and Solar Particle Investigation (COSPIN), 846; Directional Discontinuities, 848; Dust Experiment (DUST), 847; Energetic Particle Composition and Neutral Gas Experiment (EPAC), 845; Fluxgate Magnetometer (FGM), 844; Gravitational Wave Experiment (GWE), 848; Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies (HI-SCALE), 846; Magnetic Fields Experiments (VHM/FGM), 844; Mass Loss and Ion Composition, 848; Radioisotope Thermoelectric Generators (RTGs), 660, 664, 741; Solar Wind Ionic Composition Spectrometer (SWICS), 662, 845; Solar Wind Plasma (SWOOPS) Experiment, 844; Solar X-rays and Cosmic Gamma Ray Bursts, 847; Unified Radio and Plasma Wave (URAP), 845; Vector Helium Magnetometer (VHM), 844
  deployment of, 159, 241, 361, 390, 579, 661, 768; delay of, 575, 661
  development of, 660
  discoveries and scientific contributions from, 661, 662

  funding for, 785
  IMP-8 and, 686–87
  IUS launch, 71, 168, 241, 390
  Jupiter, study of by, 661, 662, 663, 842
  mission milestones, 661–63, 842
  objectives of, 579, 660, 768, 843–44
  PAM-S launch, 70, 71, 241, 390
  power for, 242, 660, 664
  solar wind study and, 265
  SPARTAN satellites and, 758–59
  Sun, study of by, 241, 265, 661–62, 663, 768, 842
Ulysses Comet Watch group, 662
Unified Radio and Plasma Wave (URAP), 845
Unified School District, Redlands, California, 408
United Kingdom/Great Britain. *See also* Compton Gamma Ray Observatory (CGRO)
  ATLAS-1 instruments, 246
  ESA membership, 279
  International Solar-Terrestrial Physics (ISTP) program, 672
  International Ultraviolet Explorer (IUE), 687–90
  payloads launched for, 21
  Roentgen Satellite (ROSAT), 136, 579, 593, 615–18, 767, 816–18
  satellites deployed for, 136, 140, 141
  Science and Engineering Research Council, 616, 684
  TRACE, 608, 812
  Yohkoh/Solar-A, 683–85, 768, 879–81
United Space Alliance (USA), 64–65
United States Human Spaceflight (NASA Monographs in Aerospace History No. 9), 238
United States Microgravity Laboratory (USML)
  USML-1, 160, 247, 265, 354, 364, 425
  USML-2, 163, 265, 354, 369, 494
United States Microgravity Payload (USMP)
  USMP-1, 161, 249, 365, 436
  USMP-2, 162, 256, 367, 464
  USMP-3, 163, 266, 370, 500
  USMP-4, 164, 272, 373, 533
United States Presidential Award for Design Excellence, 689
United States Space and Rocket Center, 406
United States-French ELV launch, 38, 39
United States-Italy Space Shuttle mission, 161
United States-Russian Commission, 297, 566
United States-Russian Cooperative Program, 255
  agreements governing, 291–93, 565
  astronaut training for, 232
  budgets and funding for, 15, 35, 213–14, 325–26, 327, 334–35
  STS-60, 255
Unity module, 192, 277, 278, 315–17, 318–20, 374, 549, 561, 562–63, 570
Universal Docking Module, 280
Universe
  age of, 641
  black holes, 599, 637, 640, 652–53, 803
  cosmic collision, 634, 635
  cosmic expansion, 643–44
  cosmic explosions, 643
  creation of, 593, 595
  expansion of, 593
Universita di Pavia, Italy, 848
Universities Space Research Association (USRA), 605
Universitt, Switzerland, 845
University Explorer mission of opportunity, 860
University of Alabama, 477, 916
University of Alabama, Birmingham, Center for Commercial Development of Space (CCDS), 378, 423, 460
University of Alabama, Huntsville, 442, 669, 773, 883
University of Alaska, 821, 822, 898
University of Arizona
  animal use and care committee, 412
  balloon flights, 910, 912
  Descent Imager/Spectral Radiometer (DISR), 978
  Galileo, 936
  Gamma-ray Spectrometer (GRS), 953
  Imager for Mars Pathfinder, 961
  Imaging Science Subsystem (ISS), 974
  Magnetometer (MAG), 945–46
  NICMOS, 831
  Spitzer Space Telescope (Space Infrared Telescope Facility [SIRFT]), 659
  Surface Stereo Imager, 969
  Thermal and evolved gas analyzer, 970
  Visual and Infrared Mapping Spectrometer (VIMS), 977
University of Bern, 806
University of Bonn, 847, 978
University of Bremen, 547
University of California, Berkeley
  balloon flights, 907, 909, 911, 914, 918, 919, 922, 924
  Cosmic Background Explorer (COBE), 791
  Electric Fields Instrument (EFI), 872
  Electron Reflectometer (ER), 945–46
  Extreme Ultraviolet (EUV) Spectrograph, 764
  Extreme Ultraviolet Explorer (EUVE), 595, 596, 793
  Far Ultraviolet Spectroscopy Explorer (FUSE), 613, 615
  Fast Auroral Snapshot Explorer (FAST), 602, 804–5
  Solar X-rays and Cosmic Gamma Ray Bursts, 847
  sounding rocket program, 884, 885, 892
  Space Astrophysics Group, 764
  Space Sciences Laboratory, 793, 868, 872
University of California, Los Angeles, 871, 935, 936
University of California, Riverside, 907
University of California, San Diego, 802, 826, 906, 913, 922, 923
University of California, Santa Barbara, 907, 908, 909, 910, 915, 917, 918, 920
University of Chicago
  Advanced Composition Explorer (ACE), 807
  Alpha Proton X-ray Spectrometer (APXS), 962

balloon flights, 911, 913, 917, 918, 919, 920, 922
Cosmic Ray and Solar Particle Investigation (COSPIN), 846
University of Cincinnati, 905
University of Cologne, 814, 815
University of Colorado, Boulder
Extreme Ultraviolet Explorer (EUVE), 934, 935
Far Ultraviolet Spectroscopy Explorer (FUSE), 613, 615
Galileo, 936
GAS experiments, 540
Goddard High Resolution Spectrograph (GHRS), 827
Laboratory for Atmospheric and Space Physics (LASP), 605, 810
sounding rocket program, 882, 883, 885, 887, 889, 891, 892, 893, 895, 897, 899, 900, 901, 902, 905
Space Technology Research Building, 605
Student Nitric Oxide Explorer (SNOE), 592, 605, 810
Ultraviolet Imaging Spectrograph (UVIS), 977
Ulysses Comet Watch group, 662
University of Delaware
Advanced Composition Explorer (ACE), 807
balloon flights, 908, 913, 918, 922, 923, 924
University of Denver, 906, 908, 910, 913, 914, 915, 917, 918, 919
University of Giessen, 537
University of Hawaii, 936
University of Houston, 884, 891, 894
University of Iowa
Comprehensive Plasma Investigation (CPI), 863
Galileo, 936
Hot Plasma Analyzer (HYDRA), 872
Plasma Investigation Subsystem (PLS), 935
Plasma Wave Subsystem (PWS), 935
Plasma Waves Investigation (PWI), 872
Radio and Plasma Wave Science (RPWS) instrument, 976
Visible Imaging System (VIS), 874
University of Kansas, 433
University of Kent, 979
University of Kiel, 877
University of Leicester, 615, 817
University of Liege, 906, 909, 912, 915
University of Maryland
Advanced Composition Explorer (ACE), 604, 806
Institute of Physical Sciences and Technology, 868
Solar, Anomalous and Magnetospheric Particle Explorer (SAMPEX), 598, 797
Solar Wind and Suprathermal Ion Composition Experiment (SMS), 868
Space Experiment Module (SEM) program, 548
Ulysses, 845
University of Michigan
balloon flights, 911
GAS experiments, 537, 551
sounding rocket program, 883, 887, 888, 891, 892, 893, 898, 901
University of Minnesota
balloon flights, 906, 907, 911
sounding rocket program, 884
University of Moncton, 543
University of New Hampshire
Advanced Composition Explorer (ACE), 807
Cooperative Astrophysics and Technology Satellite (CATSAT), 592
sounding rocket program, 884, 892, 894, 898, 902
University of New South Wales, 919
University of Pittsburgh
balloon flights, 918
sounding rocket program, 882, 884, 887, 889, 890, 891, 892, 893, 896, 898, 900
University of Southern California, 883, 886, 899, 901, 903
University of Tennessee, Center for Space Transportation and Applied Research (CSTAR), 48–49
University of Texas, Austin, 828
University of Texas, Dallas, 904
University of Tokyo, 850, 880
University of Turku, 877
University of Utah, 529, 911
University of Utrecht, 840
University of Washington
balloon flights, 909, 910, 911, 913, 914, 915, 916, 917, 918
GAS experiments, 434
sounding rocket program, 892, 902
Ultraviolet Imager (UVI), 873
University of Wisconsin, Madison
Diffuse X-ray Spectrometer (DXS), 755
High Speed Photometer (HSP), 828
Net Flux Radiometer (NFR), 709, 933
sounding rocket program, 897, 900, 901, 902
Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), 753, 982
Unmanned Launch Vehicles and Upper Stages office (Office of Space Flight), 24–25
Upper Atmosphere Research Satellite (UARS), 244, 363, 411, 691
Upper stages
budgets and funding for, 34, 35, 89, 90, 91, 97
purpose of, 70
responsibility for, 26, 27, 29, 582
types of: Centaur upper stage, 70, 71, 72, 73, 167; inertial upper stage (IUS), 69, 71, 72, 74, 167–68; payload assist module (PAM), 69, 70, 71
Uranus, 748, 749, 980
USA SAFER, 551
User Support Structure Payloads, 448
Usuda Deep Space Center, 675
Utah State University
GAS experiments, 222, 473, 507, 529, 543
sounding rocket program, 888, 890, 899, 903, 904
Utsman, Thomas, 27, 28

V

Van Allen belts, 579, 708, 723, 820
Van Allen, James, 936
Vandenberg Air Force Base
  GAS experiments, 451
  launches from, 21; Athena ELVs, 41; Atlas ELVs, 44; Clementine, 721, 948; COBE, 791; FAST, 804; payload characteristics for ELVs, 41; Pegasus ELVs, 55; Polar, 871; SAMPEX, 796; Scout ELVs, 58–59; SNOE, 810; SWAS, 814; Taurus ELVs, 61; Titan ELVs, 62; TRACE, 812
Vanguard missiles, 58
VanLandingham, Earl, 27
Variability of Solar Irradiance and Gravity Oscillations (VIRGO), 878
Veach, Charles Lacy
  STS-39, 362, 401
  STS-52, 365, 435
Vector Helium Magnetometer (VHM), 844
Vedrenne, Gilbert, 861
Venneri, Samuel, 29
VentureStar, 85, 86, 87, 88, 173, 182, 320
Venus
  Astro-2, 755, 986
  Cassini-Huygens and, 742
  exploration of, 575
  Magellan, 694–700, 701, 928–29
  Pioneer Venus (Pioneer 12), 747–48
Venus Earth-Earth Gravity Assist (VEEGA), 703, 932
Vermont Composites, 61
Vernikos, Joan, 211
Vest, Charles, 294, 565
Vest Panel, 294n129, 565
Veterans Affairs, Department of, 37
Veverka, Joseph, 939–40
Video Guidance Sensor, 760–61
Viking Mars Lander missions, 397, 576, 724, 728, 741, 966
Villafranca Satellite Tracking Station, Spain, 688, 689
Viral infections, 550
Virginia Parent Teachers and Students Association, Accomac, Virginia, 544
Virginia Space Grant Consortium, 918, 924
Virtual Environment Generator (VEG), 275
Visible Imaging System (VIS), 679, 680, 874
Visual and Infrared Mapping Spectrometer (VIMS), 977
Visual Function Tester (VFT), 381, 384, 387, 414, 421, 439, 468, 490
Visualization in an Experimental Water Capillary Pumped Loop (VIEW-CPL), 515
Voice Command System (VCS), 390
von Rosenvinge, Tycho, 797, 798, 806, 867
von Zahn, Ulf, 933
Vortex Ring Transit Experiment (VORTEX), 537
Voss, James S.
  dogtag, 265
  STS-44, 363, 413
  STS-53, 365, 438
  STS-57, 449
  STS-69, 265, 357, 369, 491
Voss, Janice E.
  STS-57, 366
  STS-63, 368, 482
  STS-83, 372, 521
  STS-94, 372
Vought Corporation (LTV Corporation), 151
Voyager missions
  areas explored by, 575, 661, 710, 740
  discoveries and scientific contributions from, 739, 748–49, 934
  events, 980
  IMP-8 and, 686–87
  Infrared Interferometer Spectrometer (IRIS), 974
  Magellan and, 697
  Radioisotope Thermoelectric Generators (RTGs), 741
  Voyager 1, 748, 750, 980
  Voyager 2, 748–49, 750, 980
  Voyager Interstellar Mission, 749, 980

W

Waite, J. Hunter, 973–74
Wakata, Koichi, 370, 498
Wake Shield Facility (WSF)
  WSF-1, 162, 255–56, 367, 460, 463
  WSF-2, 163, 265, 369, 491
  WSF-3, 269, 371, 515
Walker, David M.
  dogtag, 265
  STS-30, 360, 379
  STS-53, 365, 438
  STS-69, 265, 369, 491
Wallops Flight Facility, Virginia
  balloon flights, 693, 907, 908, 909, 910, 911, 912, 913, 914, 915, 916, 917, 918, 921, 924, 925
  COBE, 595
  launches from, 21; commercial launches, 48; Conestoga ELVs, 49; HETE/SAC-B, 671, 860; Pegasus ELVs, 55; Scout ELVs, 59
  sounding rocket program, 692, 883, 884, 887, 888–89, 891, 892, 894–95, 898, 899, 901, 902–3, 905
Walter, Ulrich, 366, 444
Walter Reed Army Institute of Research, 421
Walz, Carl E.
  STS-51, 253, 357, 366, 453
  STS-65, 367, 469
  STS-79, 371, 512
Wanke, Henry, 962
Waseda University, 864
Washington University, St. Louis, 806, 911, 919, 922
Water Recovery System, 308, 568
Wave Complex, 965
Weber, Mary Ellen, 369, 489
Weedman, Daniel, 582, 584
Weiler, Edward J., 584, 651, 738
Weilheim, Germany, 617

Weldmac, 178
Werkstofflabor (WL) Material Sciences Laboratory, 445–46
Wescott, Gene, 821, 822
West Richland Elementary School, Nobel, Illinois, 548
WESTAR (Woodmore Elementary School, Mitchellville, Maryland), 544, 548
Westphal, James A., 824
Wetherbee, James D.
  STS-32, 361, 385
  STS-52, 365, 435
  STS-63, 368, 482
  STS-86, 373, 531
White House. *See* President of the United States
White Light Coronograph, 757–58, 987
White Sands Missile Range
  DC-XA, 81, 173
  sounding rocket program, 882–905
  TDRS data, 600
  X-34, 82, 84
White Sands Space Harbor (Northrup Strip), 237
White Sands Test Facility, 82
Whitten, Raymond, 212
Wicomico High School, Salisbury, Maryland, 544
Wide Angle Camera (WAC), 974
Wide Band Spectrometer (WBS), 684, 881
Wide Field and Planetary Camera (WFPC), 357, 459, 621, 623, 628, 824
  WFPC2, 459, 627–28, 829
Wide field cameras (WFCs)
  Astro-1, 396, 750–51
  BeppoSAX, 855
  Roentgen Satellite (ROSAT), 615, 616, 617, 817
Wide-Field Infrared Explorer (WIRE), 591–92
Wide-field X-ray Monitor (WXM), 861
Wiedenbeck, Mark, 807
Wilcutt, Terrence W.
  STS-68, 368, 476
  STS-79, 371, 512
  STS-89, 373, 536
Wilhelm, Klaus, 876
Williams, D. J., 935
Williams, Dafydd (David) Rhys, 275, 374, 538
Williams, Donald E., 360, 382
Williams, Richard, 212
Wind, 50, 139, 579, 672, 673, 674, 675, 676–78, 769, 866–70
Windmill experiment, 697
Window Experiment (WINDEX), 483, 490
Windward Islands, 428
Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), 396, 485, 750–51, 753, 754, 982, 986
Wisniewski, Richard J., 24, 25, 28
Wisoff, Peter J.K.
  STS-57, 252, 356, 366, 449
  STS-68, 368, 476
  STS-81, 371, 517
Withbroe, George, 580, 581, 584
Wolf, David A.
  aboard *Mir*, 272, 274, 304, 531, 536, 555
  STS-58, 366, 455
  STS-86, 272, 373, 531
  STS-89, 274, 373, 536
Woodgate, Bruce E., 829
Woodmore Elementary School, Mitchellville, Maryland (WESTAR), 544, 548
Woomera, Australia, 899–900, 903
Worcester Polytechnic Institute, 407

X

X-24 wingless lifting body, 321
X-30 program, 79–80
X-33
  budgets and funding for, 90, 92, 102
  cancellation of, 88, 186
  characteristics of, 87, 171
  construction area damage, 177
  development and construction of, 80, 85–86, 172, 173, 174, 175, 178, 179, 181, 184, 185
  investigations of, 87–88, 185
  launch facility, 86, 175, 177, 178, 179, 180, 184, 185
  management of, 32, 178, 181, 182
  reviews of, 180
  technology development, 81
  testing of, 86, 174, 175, 176–77, 179, 181, 182, 183
  VentureStar compared to, 87
X-34
  budgets and funding for, 92, 103
  cancellation of, 186
  characteristics of, 82–83, 171
  development of, 80, 82, 172, 173, 177, 180
  management of, 32, 181
  technology development, 81
  testing of, 83–84, 176
X-38 Crew Return Vehicle, 279, 310, 320–23, 568, 570
X-band Synthetic Aperture Radar (X-SAR), 256, 257, 477
X-ray Nova Scorpii (GRO J1655-40), 649
X-ray sources, 575
X-ray Spectrometer (XRS), 941
X-ray telescope (XRT)
  Advanced Satellite for Cosmology and Astrophysics (ASCA), 665, 849–50
  Roentgen Satellite (ROSAT), 615, 617, 817
X-ray Timing Explorer, 599. *See also* Rossi X-ray Timing Explorer (RXTE)
X-ray/Gamma-ray Spectrometer (XGRS), 940, 941

Y

Yale University, 906, 907, 909, 914, 918, 919, 920
Year of the planets, 575
Yelstin, Boris, 291, 292, 297, 565
Yeomans, Donald K., 942
Yohkoh/Solar-A, 683–85, 768, 879–81
Young, A. Thomas, 304
Young, David T., 858, 973
Young, John, 516

Yuma Proving Grounds, 321
Yuri Gagarin Cosmonaut Training Center, 232

Z

Zarnecki, John C., 979
Zarya module, 192, 277, 278, 280, 315, 316–17, 319–20, 549, 561, 562–63, 570
Zentrum fur Angewandte Raumfahrttechnologie und Mikrogravitation (ZARM), 547
Zero Gravity Growth of Ice Crystals, 383
Zombeck, Martin, 817
Zuber, Maria T., 942

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